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Risk assessment model for the introduction of non-native freshwater fish into New Zealand

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Summary

A risk assessment model was developed to score the potential risk for both the establishment and impact of introduced freshwater fish species in New Zealand. Although based on similar models developed for Australia and the UK, it is customised to a New Zealand context in which the risk of a site-specific ecological impact is of more concern than the potential for a species to spread rapidly and widely (i.e. its invasiveness). The model was calibrated using data on 21 introduced fish species already present in New Zealand and tested on eight species not present but for which a decision on introduction has been made using other methods. Threshold scores for risk of establishment, risk of impact and overall risk of causing ecological damage were set based on current knowledge and incorporated into a decision support system to provide managers with a numerical (vs subjective) basis for deciding on whether or not to permit the entry of a new species. The model assists in decision-making on the introduction of new species and also provides a means of assessing the ecological risk posed by the further spread of those introduced fish already present.

Introduction

New Zealand's freshwater fish fauna is currently characterised by relatively few species, a high level of endemism and a high proportion of introduced species (McDowall, 1990). It is therefore no surprise to find that it is listed as one of the six global 'hotspots' where the proportion of introduced species to native species exceeds 25% (Leprieur et al., 2008). Despite increasing evidence that the introduced species can adversely affect native fish and ⁄ or natural environments (e.g. McDowall, 1984a, 1987; Allibone and McIntosh, 1999; Rowe and Graynoth, 2002; Closs et al., 2004), there is no slowing in the decadal rate of new introductions to New Zealand (Fig. 1).

The problem posed by the introduction of new species is not confined to freshwater fish, nor to New Zealand. A number of OECD countries have now developed legislative mechanisms to reduce the onslaught of introduced species introductions and, in New Zealand, the statutory framework for border control is provided by the Hazardous Substances and New Organisms Act 1996 (HSNO 1996). This Act confers the Environmental Risk Management Authority (ERMA) with the power to permit or prohibit the entry of introduced organisms into New Zealand. Sections 35 and 36 of this Act charge ERMA with carrying out a rapid assessment of risk and permitting an organism's entry if it is improbable that it will: (i) form a self-sustaining population, (ii) displace a valued or endemic species, (iii) affect endemic genetic diversity, (iv) result in habitat deterioration, (v) create a disease problem, or (vi) adversely affect human health and safety. These are all valid potential impacts, but there is no guidance in the legislation on how they are to be assessed. The HSNO Act also denies entry for 'prohibited species', which are listed in Schedule 2, and prohibits the entry of 'unwanted organisms', as defined in the Biosecurity Act (1993). Under the Biosecurity Act, a species can be declared 'unwanted' (Section 146c) if a Chief Technical Officer believes the organism is capable of causing unwanted harm to any natural and physical resource, or human health (see Section 2). However, there is often a dearth of scientific information on the potential effects of an alien species and a declaration of 'unwanted' could be legally challenged if there is no basis to support the 'belief' that it will be harmful. In the absence of such information, a rapid and objective method for assessing a species' potential ecological harm in New Zealand is required. Such a risk assessment needs to be based on information already available (i.e. a desk-top assessment), must address the legislative requirements for permitting the entry of new freshwater fish species into New Zealand, and should provide an objective basis for defining 'unwanted' species.

Desk-top risk assessments for freshwater fish have now been developed for the USA, Australia and the UK (viz., Kolar and Lodge, 2002; Bomford and Glover, 2004; Copp et al., 2005) as well as for specific regions within Australia (Clunie et al., 2002; Webb, 2006). These models generate numeric scores for a given species based on an assessment of the key traits associated with known pest fish species. These include a broad diet, rapid reproduction, high dispersal ability, wide physiological tolerances, ability to hybridise with natives as shown by hybridisation in other circumstances, the potential to cause habitat alteration and a high loading of non-native parasites and disease organisms (Li and Moyle, 1981; Taylor et al., 1984; Miller, 1989). Risk assessments based on these traits (e.g. Bain, 1993) focus mainly on the risk of environmental impact. However, more recent risk assessments for freshwater fish have focused more on traits associated with invasive potential (e.g. Kolar and Lodge, 2002; Bomford and Glover, 2004; Kolar, 2004; Copp et al., 2005; Ruesink, 2005). These include rapid growth, early maturity, short life-span, high fecundity, no parental care (i.e. r-selected traits), a large native range, phenotypic plasticity; wide physiological tolerances; gregariousness; high propagule pressure and a prior history of invasion success elsewhere (e.g. Ricciardi and Rasmussen, 1998; Marchetti et al., 2004a,b; McDowall, 2004).

In terrestrial environments, invasiveness [i.e. the ability to spread widely and establish large, self-recruiting populations,

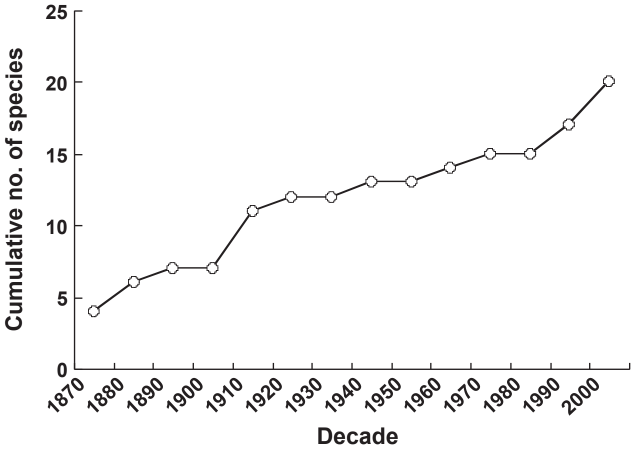

Fig. 1. Cumulative, decadal increase in number of introduced freshwater fish species established in New Zealand

or achieve 'stage V' in Colautti and MacIsaac's (2004) classification] can provide a good analogue for impact (Parker et al., 1999; Pheloung et al., 1999; Kolar and Lodge, 2001; Levine et al., 2003). Terrestrial species generally create major environmental problems when they can spread rapidly, occupy a wide geographic range, and become abundant within this range. As a result, invasiveness is often regarded as more important for introduced species than the ability to create site-specific impacts. But Ricciardi and Cohen (2006) point out that 'invasiveness' does not predict impact. This is more so for freshwater species, especially in an island nation such as New Zealand, which is characterised by many short rivers (McDowall, 2004) and high coastal salinity concentrations that reduce the risk of natural dispersal and spread between catchments. The dispersal and spread of most freshwater fish between river basins in New Zealand is constrained by salinity at the river mouth (McDowall, 1990), and human vectors are required to transfer freshwater fish from one basin to another. Invasive traits of introduced fish are therefore of less concern than their ability to create impacts. For example, rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) populations are, with few exceptions, non-anadromous in New Zealand, and have been spread widely by human vectors (McDowall, 1984b, 1990). As piscivores they have reduced populations of native galaxiids in many lakes and streams (McDowall, 1990; Townsend and Crowl, 1991; McIntosh, 2000). Similarly, the spread of gambusia (*Gambusia affinis*) is related primarily to human vectors but it is not invasive because it is currently limited to the North Island, is spatially restricted to shallow, low velocity waters, and is temporally restricted to summer months when water temperatures are high (> 20°C). Nevertheless, it has reduced a rare and threatened galaxiid in several lakes (Rowe, 2003) and has affected the depth distribution of another (Rowe et al., 2007). Impacts of introduced fish on endemic biodiversity in New Zealand are therefore often site-specific and related to species interactions rather than to invasiveness. Similarly, Moyle and Light (1996) observed that, for introduced freshwater fish, impacts were linked to location-specific interactions not 'invasiveness'.

A fish risk assessment model for New Zealand therefore needs to emphasise the potential for ecological impact over invasiveness. But the risk of a new species becoming established and spreading still needs to be considered and must encompass the multiple stages involved in a species' invasion as noted by Kolar and Lodge (2002), Colautti and MacIsaac (2004), and Marchetti et al. (2004a,b), as well as the various elements of propagule pressure (Simberloff, 2009).

In assessing the potential for ecological impacts in a New Zealand context, a risk assessment cannot be restricted to just loss of endemic biodiversity and / or the degradation of fish habitats. Ecosystem changes are also important. For example, recent studies have revealed that the herbivorous rudd (*Scardinius erythrophthalmus*) can change the macrophyte community composition in New Zealand lakes (Hicks, 2003; Neilson et al., 2004), and rudd destroyed a stocked trout fishery by out-competing trout for an anglers' lures resulting in the decline of this apex predator (Rowe and Champion, 1994). In addition, multi-species introductions of fish that include planktivores, herbivores, and benthivores have reduced water clarity in New Zealand lakes and accelerated eutrophication (Rowe, 2007; Schallenberg and Sorrell, 2009). An assessment of the environmental impact potential for introduced freshwater fish in New Zealand therefore needs to include impacts related to effects on lake and river ecosystems as well as impacts on indigenous biodiversity, aquatic habitats and fisheries.

Using all these criteria, a risk assessment model was developed for New Zealand and calibrated using information on 21 introduced species already present. It was tested on eight species not present but for which some independent assessment of impact risk was available. The model manages the uncertainty due to lack of data and variability between respondents by taking a precautionary approach and assigning the highest likelihood of impact. In this context, a precautionary approach is one where a decision cannot be made because of a lack of data and so the burden of proof (that there will be no harm) is assigned back to those proposing to introduce a new species. A decision support system is provided to allow a rapid assessment of overall risk based on the risk of establishment and the likelihood of impacts.

Materials and methods

Questions in the risk assessment models developed by Bomford and Glover (2004) for Australia and by Copp et al. (2005) for the United Kingdom were used as a basis for the New Zealand fish risk assessment model. The existing questions were modified and customised to a New Zealand context, or deleted where not appropriate. Additional questions were added to reflect the statutory criteria and ecological context for a New Zealand model. Questions addressing the risk of a new species becoming established and spreading (i.e. a self-recruiting population develops at one location and then spreads) were separated from those that address the risk of an ecological impact occurring so that the risk of establishment (and spread) could be assessed independently of the risk of impact. The full list of questions is provided at http://www.niwa.co.nz/our-science/aquatic-biodiversity-and-biosecurity/tools/freshwater-management.

Each question was worded so that a yes / no / unsure response was possible. A scoring system was then developed, with a high score indicating greater risk. Weighting of the scores was carried out to reflect the greater or lesser importance of certain traits over others. For example, piscivory is more of a threat to New Zealand's relatively impoverished and ancient native fish fauna than omnivory. Similarly, an inability to breed in New Zealand waters would negate the scores for most other traits relating to establishment. Where the answer to a question could not be provided because of a lack of information, the precautionary principle was used to set the score at the maximum value. The scoring schedule for each question is provided at the web link: http://www.niwa.co.nz/our-science/aquatic-biodiversity-and-biosecurity/tools/freshwater-management.

The model was calibrated using existing data for the 21 species of introduced fish now established in New Zealand. These include seven salmonid, seven cyprinid, five poecillid, one percid, and one ictalurid species (Table 1). Total scores for both the risk of establishment and risk of impact were initially calculated using expert assessment (concensus approach by three scientists) based on a literature search (e.g. FishBase, and reports of the species in Australasian waters). Their assessment revealed the need for refinement of several questions and the addition of new ones, so the model was adjusted and the scores re-calculated. Threshold scores for high, medium and low risks of establishment and impact, respectively, were then set using information on the current status of the 21 species in New Zealand waters. To quantify the current extent of geographic spread for each species, its presence in each of the 314 NZMS260 topographical maps that each cover 120 km^2 and collectively include the entire country was determined from data held in New Zealand Freshwater Fish Database (McDowall and Richardson, 1983). The percentage of maps in which it was present was calculated, and the extent to which each of the 21 introduced species have spread throughout New Zealand was deemed to be low for species in two or less maps, high for species in 20 or more maps, and medium for species between these limits. These qualitative indicators of spread for the introduced species were compared with the scores for risk of establishment to identify threshold values for low, medium and high risk species respectively.

Similarly, the known environmental impacts of each of the introduced species were identified from the existing literature and each species classified as having a relatively high, medium, or low ecological impact depending on the range of impacts reported. Species reported to adversely affect two or more categories of environmental impact (e.g. a reduction in endemic species, degradation of habitat, decrease in water quality, decline in macrophytes, or interference with fisheries) were deemed to have a high risk of impact. Conversely, species for which there were no reported adverse impacts, despite being present for more than several decades, were deemed to have a low risk of impact because any adverse effect would have been noted within such a timeframe. Species affecting only one category of impact therefore pose a medium risk. These qualitative ratings were compared with the numeric scores for risk of impact to identify threshold values for low, medium and high risk species, respectively.

The overall impact of an introduced species is the product of its range and abundance (i.e. its establishment and invasiveness) and the effect that an individual has on the ecosystem (Parker et al., 1999). Recent risk assessment guidelines developed for introduced aquatic species in North America (e.g. Hammond, 2009) therefore address the probability of an organism becoming established as well as the probability that its establishment will result in adverse ecological consequences. The score defining a species' risk of establishment in New Zealand was combined with the score for risk of impact to develop an overall ecological risk score. The three scores were then used in a decision support system. This provides three decision options (allow introduction, prohibit introduction, defer the decision until more information is obtained). Where a species has a low risk of establishment and a low risk of impact, it is deemed to be relatively benign and entry can be contemplated (dependent on other factors such as disease importation risk, negative cost-benefit analyses, or socio-cultural objections). Where a species has a high risk of establishment and a high risk of impact it is deemed to be potentially harmful and entry would be denied. Species between these two extremes would be denied entry until a full and more comprehensive Assessment of Environmental Effects (AEE) report had been produced to show that the rapid assessment of risk provided by the Fish Risk Assessment

Table 1
Comparison between qualitative extent of spread (high, medium, or low) based on actual measures of geographic distribution in New Zealand and FRAM scores for potential risk of spread for 21 introduced fish species currently present in the wild in New Zealand

Common name	Scientific name	Total database records (N)	NZMS260 maps where present (N)	NZMS260 map occurrence (%)	Actual extent of spread (H / M / L)	FRAM establishment risk score (N)
Swordtail	*Xiphophorus helleri*	1	1	0.32	L	2
Sailfin molly	*Poecilia latipinna*	1	1	0.32	L	2
Caudo	*Phalloceros caudimaculatus*	1	1	0.32	L	5
Orfe	*Leuciscus idus*	1	1	0.32	L	13
Mackinaw	*Salvelinus namaycush*	1	1	0.32	L	6
Atlantic salmon	*Salmo salar*	1	1	0.32	L	8
Guppy	*Poecilia reticulata*	4	2	0.64	L	2
Sockeye salmon	*Oncorhynchus nerka*	7	4	1.28	M	11
Silver carp	*Hypophthalmichthys molitrix*	10	6	1.90	M	7
Grass carp	*Ctenopharyngodon idella*	54	14	4.43	M	3
Tench	*Tinca tinca*	113	27	8.54	H	14
Brook char	*Salvelinus fontinalis*	168	28	8.86	H	13
Brown bullhead	*Ameiurus nebulosus*	288	28	8.86	H	15
Koi carp	*Cyprinus carpio*	153	30	9.49	H	14
Rudd	*Scardinius erythrophthalmus*	261	47	14.87	H	14
Gambusia	*Gambusia affinis*	780	60	18.98	H	13
Chinook salmon	*Oncorhynchus tshawytscha*	332	61	19.30	H	9
Perch	*Perca fluviatilis*	384	65	20.57	H	14
Goldfish	*Carassius auratus*	640	86	27.22	H	14
Rainbow trout	*Oncorhynchus mykiss*	1828	144	45.57	H	13
Brown trout	*Salmo trutta*	6845	233	73.73	H	13

Model (FRAM) was either too precautionary or clearly that it overestimated the risk of impact.

This model for risk assessment was subsequently tested on eight species of fish not now present in New Zealand but for which some independent assessment of ecological impact has already been made. These included the two freshwater fish species on the list of prohibited species included in the HSNO Act (i.e. sticklebacks *Gasterosteus* sp., and pike *Esox lucius*), two aquarium species (white-cloud mountain minnow *Tanichthys albonubes* and weather loach *Misgurnus anguillicaudatus*), roach (*Rutilis rutilis*), largemouth bass (*Micropterus salmoides*), channel catfish (*Ictaluris punctatus*) and gudgeon (*Gobio gobio*). The FRAM scores for all of these species were calculated and examined to determine whether a decision based on the scores would concur with the decisions already made.

Results

The scores for the risk of establishment for the 21 species of introduced fish present in New Zealand were positively correlated with the scores for risk of impact ($r = 0.64$, $P < 0.01$) (Fig. 2), but silver carp (*Hypophthalmichthys molitrix*), tench (*Tinca tinca*), goldfish (*Carassius auratus*) and brook char (*Salvelinus fontinalis*) could be considered outliers. Silver carp had a low risk of establishment despite a high risk of impact because this species can potentially reproduce only in the Waikato River (Rowe, 2010). It has a low risk of establishment at a national level but its predicted impact would be high if it did become established (Rowe, 2010). In contrast, tench, goldfish and brook char all had relatively low risks of impact even though their risk of establishment is high. For tench and especially goldfish, this reflects their wide distribution in New Zealand (McDowall, 1990) coupled with the absence of any reported environmental impacts (Rowe and Graynoth, 2002; Rowe, 2004). These outliers show that a high risk of impact is not always related to a high risk of establishment.

The measure of current geographic distribution (% map occurrence) was positively correlated ($r = 0.47$, $P < 0.05$) with the score for risk of establishment (Table 1). All species with a high level of geographic spread had scores over 12, except chinook salmon (*Oncorhynchus tshawytscha*). This exception arises because breeding populations of this species have only established in major rivers on the east coast of the South Island despite widespread liberations of this fish in the early 1900s (McDowall, 1990). Chinook salmon are diadromous, and strays result in the occurrence of isolated fish in many other rivers throughout much of the country. Hence it has a widespread occurrence but its breeding populations are restricted to a much smaller area.

Species with a low level of geographic spread all tended to score below 6 for risk of establishment, except for orfe (*Leuciscus idus*) and Atlantic salmon (*Salmo salar*). The relatively low geographic spread for orfe reflects its recent arrival and the fact that it is present in only one known location. Similarly, Atlantic salmon now occur as a landlocked population in only one South Island catchment (McDowall, 1990). Its spread via anadromy is not possible and, although translocated populations could potentially develop breeding stocks in other lakes, it can now only be spread more widely by anthropogenic vectors. Hence its low current distributional status does not represent potential for wider dispersal in the future.

Species with a medium level of geographic spread had risk of establishment scores that were over 6 but <12; the one exception was grass carp (*Ctenopharyngodon idella*). A self-recruiting population of this fish has not established in New Zealand and is only theoretically possible in the Waikato River. However, even here, breeding is improbable (Rowe and

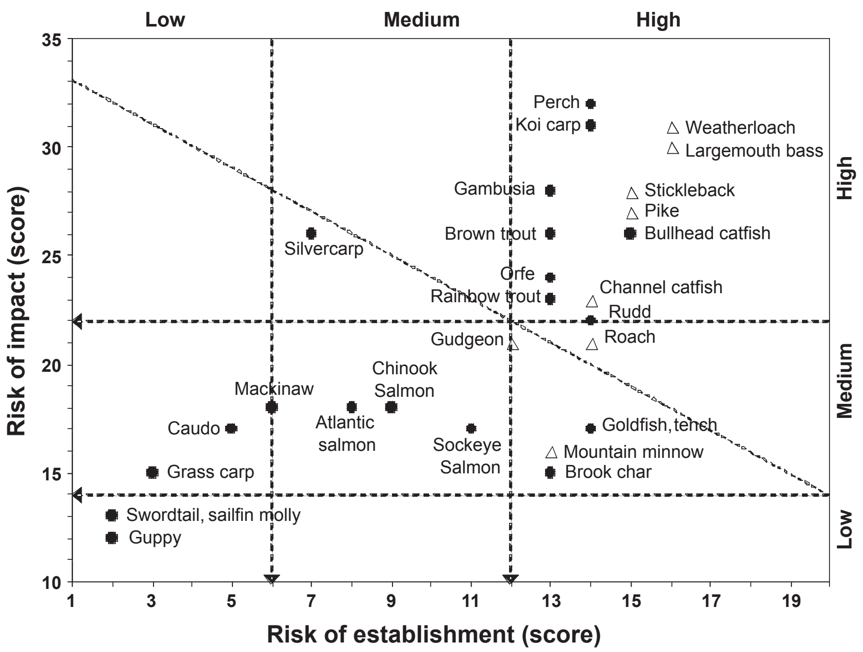

Fig. 2. Plot of FRAM scores for risk of establishment and risk of impact for each introduced freshwater fish species currently present in New Zealand (solid circles) and for species not present in New Zealand but for which decisions on potential impact have already been made (open triangles). Horizontal and vertical dashed arrows respectively indicate threshold scores for a high, medium and low risk of impact and high medium and low risk of establishment. Dashed diagonal line indicates total score (risk of establishment plus risk of impact) above which a species entry would be prohibited

Table 2
Comparison between FRAM scores for predicted risk of impact for 21 introduced fish species currently present in New Zealand and a qualitative assessment of their known impact based on reports of impacts on key components of aquatic environments. The qualitative extent of impact (high, medium, or low) is based on the range and number of impacts reported

	Reports of adverse impacts on key components of aquatic environments						
Species	Fish fauna	Habitats	Water quality	Macrophytes	Fisheries	Extent of impact (H / M / L)	FRAM score
Swordtail						L	13
Sailfin molly						L	13
Caudo						L	17
Orfe						L	24
Mackinaw						L	18
Atlantic salmon						L	18
Guppy						L	12
Sockeye salmon	5					M	17
Silver carp						L	26
Grass carp				14, 15		M	15
Tench			19, 20			M	17
Brook char						L	14
Brown bullhead	1		19, 20	23		H	26
Koi carp		6	19, 20	6		H	32
Rudd			19, 20	9, 25, 26	15	H	22
Gambusia	2, 17, 18					M	28
Chinook salmon	7					M	18
Perch	3, 24		19, 20, 21, 27			H	31
Goldfish			19, 20			M	17
Rainbow trout	10, 16, 22				10	H	23
Brown trout	4, 10, 11, 12, 22	8, 11, 13				H	26

1. Barnes (1996), 2. Barrier and Hicks (1994), 3. Closs et al. (2003), 4. Crowl et al. (1992), 5. Graynoth et al. (1986), 6. Hanchet (1990), 7. James and Unwin (1996), 8. Huryn (1996), 9. Lake et al. (2002), 10. McDowall (1990), 11. McDowall (2003), 12. McIntosh (2000), 13. McIntosh and Townsend (1995), 14. Rowe and Schipper (1985), 15. Rowe and Champion (1994), 16. Rowe and Chisnall (1997), 17. Rowe (2003), 18. Rowe et al. (2007), 19. Rowe (2007), 20. Schallenberg and Sorrell (2009), 21. Smith and Lester (2006), 22. Townsend and Crowl (1991), 23. Dugdale et al. (2006), 24. Rowe and Smith (2002), 25. Hicks (2003), 26. De Winton et al. (2003), 27. Rowe and Smith (2003).

Schipper, 1985) and has not occurred despite escapement of stocked fish. Artificially propagated grass carp have been widely stocked for weed control in a number of New Zealand lakes, resulting in a wide distribution, but an inability to breed gives it a low risk of establishment.

The known impacts for the various species in New Zealand waters are listed in Table 2 along with a qualitative assessment of impact potential (low, medium, high), based on the number and range of impacts reported to have occurred to date. Notable differences between the qualitative assessment of environmental impact and the FRAM score occurred for only three of the 21 species (gambusia, silver carp and orfe). For each of these species the FRAM score was higher than the assessment, based on reported impacts. Lack of studies addressing the actual impact of silver carp and orfe in New Zealand is responsible for two of these exceptions. The low rating for the impact of gambusia was because, in New Zealand, it has only been reported to affect some native fish, whereas in other countries it is also implicated in reducing water quality and amphibians.

The mean FRAM score (and range) for the species with respectively low, medium and high levels of actual spread and of impact in New Zealand (excluding the exceptions noted above) are shown in Table 3. These values were used to define threshold values for establishment and impact risk (Fig. 2), with the intersections of the threshold lines indicating the respective minimum and maximum FRAM scores for acceptable (< 20) and unacceptable (> 34) risk of entry. Decisions on entry related to these threshold scores and to the maximum and minimum total scores are shown in the decision support system (Fig. 3). Species with total scores between the two extremes (i.e. 21–33) require a comprehensive Assessment of Environmental Impact (AEE) report to show that the rapid assessment of risk score from FRAM was overestimated, before entry can be allowed.

Environmental risk assessments carried out prior to the FRAM analysis concluded that largemouth bass (McDowall, 1968), channel catfish (Townsend and Winterbourn, 1992), weatherloach (Corfield et al., 2008) and roach (Rowe et al., 2008) could readily become established in New Zealand and

Table 3
FRAM scores and threshold values for introduced species with respectively low, medium and high levels of actual geographic spread and reported impacts in New Zealand

	Extent of geographic spread			Range of reported impacts		
	Low	Medium	High	Low	Medium	High
Number of species	5	2	13	7	5	6
Mean FRAM score	3.4	10.0	13.7	15.0	16.8	26.7
Range of scores	2–6	9–11	13–15	12–18	15–18	23–32
Threshold values	0–6	7–11	12–40	0–14	15–21	22–40

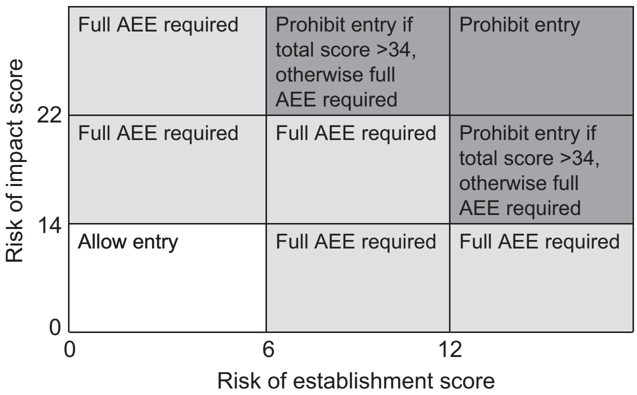

Fig. 3. Decision Support System (DSS) for Fish Risk Assessment Model (FRAM) based on threshold scores for high, medium and low risk of establishment and high, medium and low risk of impact (see Fig. 2). A full Assessment of Environmental Effects (AEE) report provides a more comprehensive review of the species biology, ecology, reported impacts overseas and key gaps in information in order to provide a formal, as against a rapid, assessment of environmental risk.

would have the capacity to cause significant ecological damage. Decisions were therefore made to deny their entry and, where required, to destroy any existing stocks. No reported assessments were carried out for pike and stickleback, but both were included in the list of prohibited species in the HSNO (1996) Act because there was little doubt that they would readily establish in New Zealand; hence, a decision was made to deny their entry. A large, top-level piscivore such as pike would pose a new threat to native fish species already decimated by brown and rainbow trout, whereas sticklebacks can be expected to compete with native fish for invertebrate prey, and are known to prey on demersal fish eggs and larvae. In contrast, an environmental risk assessment prepared for the white-cloud mountain minnow (Corfield et al., 2008) indicated that whereas it could well become established in Australia and New Zealand, it was unlikely to cause significant ecological harm as it is relatively small (< 40 mm), is not piscivorous and does not have a reputation for aggression; consequently its introduction is not prohibited and aquarium stocks currently exist in New Zealand. Although no studies were carried out on gudgeon in New Zealand, the single population was eradicated by the Auckland Regional Council, as it was the only known population in New Zealand and was declared 'unwanted' as a precautionary measure. This declaration now prevents the entry of this species. The FRAM scores for the eight introduced fish species that are not now present in New Zealand indicated that none of these species, apart from gudgeon and white-cloud mountain minnow, would be allowed entry to New Zealand (Fig. 2). There is therefore agreement between decisions based on the FRAM scores and the historic decisions on entry for seven of the eight alien fish species not present in New Zealand. This agreement provides confidence in the use of FRAM as a rapid, desk-top method to provide an objective risk assessment for introductions of freshwater fish to New Zealand. The decision to eradicate gudgeon was a precautionary approach based on the lack of any data or risk assessment.

Discussion

The Fish Risk Assessment Model (FRAM), developed for New Zealand, differs from most other risk assessment models in that it explicitly separates the risk of establishment and spread from the risk of impact. This reflects our view that 'invasiveness', defined as the 'the ability to spread widely without human intervention and to colonise a wide range of habitats over a large geographical scale' is not as critical in freshwater ecosystems as it is in terrestrial or marine ecosystems. Within terrestrial and marine ecosystems, there are few natural barriers to a new species' spread. In contrast, spread of freshwater species between river basins or lakes is prevented by land and/or salinity barriers. Invasiveness is therefore less important for freshwater fish, especially in island nations such as New Zealand, where impacts in lakes or rivers are more important and where a fish species movement from one river basin or lake to another generally requires human intervention.

FRAM also differs in that the range of impacts is extended from loss of biodiversity and the degradation of aquatic habitats, to impacts on water quality, macrophytes, plankton, food webs, and limnetic processes leading to accelerated eutrophication. Potential impacts to fisheries and human health are also included in FRAM, as is disease risk, but the latter is not emphasised as it is dealt with more comprehensively and separately under the Biosecurity Act via the Ministry of Agriculture and Fisheries' New Zealand Import Health Standard.

The Fish Risk Assessment Model therefore provides a rapid, semi-quantitative method to assess the ecological risk of allowing a non-native freshwater fish species entry into New Zealand. It also provides a tool to assess the comparative risk to aquatic environments of the already established introduced fish species and so allows prioritisation of control measures designed to halt both their spread and impact. An example of where such prioritisation is required is provided by the relatively high FRAM score for perch. Perch is scored as a high risk species for New Zealand, alongside koi carp and brown bullhead catfish. Koi carp is currently regarded as a major threat to the New Zealand environment (Hanchet, 1990). It has been the subject of much publicity and has been declared an 'unwanted organism' under the Biosecurity Act. Similarly, the spread of catfish to lakes has been the subject of much concern and publicity and a range of preventative measures to minimise accidental spread by angler's boats and trailers is now well established. Although perch has a similarly high risk of impact, its potential for harm is not generally recognised yet and its future spread is not addressed with the same level of concern. It is a valued sports fish but has been shown to affect a wide range of small, endemic fish species and decapods in Australia (reviewed in Rowe et al., 2008) and has the potential for similar impacts in New Zealand. It has reduced the abundance of common bullies in New Zealand lakes (Closs et al., 2003; Ludgate and Closs, 2003; Goldsmith, 2004), and can be expected to decimate other native fish, particularly small galaxiids and smelt in lowland, coastal lakes.

The FRAM scores for both rainbow and brown trout indicate that if these species were to be considered for introduction into New Zealand today, entry would be denied. Trout have clearly had a major impact on the New Zealand galaxiid fauna (McDowall, 2006), justifying their high FRAM scores. However, FRAM does not consider socio-economic factors involved in a decision on a species' introduction. The benefits of trout in providing freshwater fisheries in New Zealand have, in retrospect, been high and are considered by many to outweigh their ecological impacts. However, in recognising the high risk of potential ecological damage by trout, their introduction and release today would have been much more carefully planned and controlled to ensure that they were stocked only in waters where useful fisheries could be created and not into waters where significant ecological harm with little or no fishery benefit would occur, as has happened.

FRAM therefore provides decision-makers with a tool to consider the introduction of a new fish species to New Zealand. In the past, economic and social factors have tended to outweigh the ecological risks of a new introduction because the ecological risks have been difficult to quantify and are often based on subjective assessments. FRAM now provides a means to redress this by providing an objectively derived, numeric score that allows direct comparison with the scores of other species whose impact has already been measured. However, it should be emphasised that the scientific basis for predicting impacts of new species introductions on the environment is in its infancy. Predictions are therefore limited at present and better models are clearly required, but will depend on further research to better understand species interactions.

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References

Allibone, R.; McIntosh, A. R., 1999: Sports fish – native fish interactions. NIWA Client Report FGC90203.

Bain, M. B., 1993: Assessing impacts of introduced aquatic species: grass carp in large systems. Environ. Manag. **17,** 211–224.

Barnes, G. R., 1996: The biology and general ecology of the brown bullhead catfish (*Ameiurus nebulosis*) in Lake Taupo. MSc thesis, University of Waikato, Hamilton.

Barrier, R. F. G.; Hicks, B. J., 1994: Behavioural interactions between black mudfish (*Neochanna diversus* Stokell, 1949: Galaxiidae) and mosquitofish (*Gambusia affinis* Baird and Girard, 1854). Ecol. Freshw. Fish **3,** 93–99.

Bomford, M.; Glover, J., 2004: Risk assessment model for the import and keeping of exotic freshwater and estuarine finfish, Bureau of Rural Sciences, Canberra, Australia.

Closs, G. P.; Ludgate, B.; Goldsmith, R., 2003: Controlling European perch (*Perca fluviatilis*): lessons from an experimental removal. Managing Invasive Freshwater Fish in New Zealand. Proceedings of a workshop hosted by the Department of Conservation, 10–12 May 2001, Hamilton. New Zealand Department of Conservation, Wellington.

Closs, G. P.; Dean, T.; Champion, P.; Hofstra, D., 2004: Aquatic invaders and pest species in lakes. In: Freshwaters of New Zealand, Chapter 27. J. Harding, P. Mosley, C. Pearson and B. Sorrel (Eds). New Zealand Hydrological Society and New Zealand Limnological Society, Caxton Press, Christchurch, pp. 1–14.

Clunie, P.; Stuart, I.; Jones, M.; Crowther, D.; Schreiber, S.; McKay, S.; O'Conner, J.; McLaren, D.; Weiss, J.; Gunasekera, L.; Roberts, J., 2002: A risk assessment of the impacts of pest species in the riverine environment in the Murray-Darling Basin, Department of Natural Resources and Environment, Arthur Rylah Institute for Environmental Research, Melbourne.

Colautti, R. I.; MacIsaac, H. J., 2004: A neutral terminology to define invasive species. Diversity Distrib. **10,** 135–141.

Copp, G. H.; Garthwaite, R.; Gozlan, R. E., 2005: Risk identification and assessment of non-native freshwater fishes: concepts and perspectives on protocols for the UK. J. Appl. Ichthyol. **21,** 371–373.

Corfield, J.; Moore, A.; Diggles, B.; Richards, A.; Jubb, C.; McDowall, R.; Rowe, D., 2008: Review of the impacts of introduced aquarium fish species that have established wild populations in Australia. Australian Government Department of the Environment, Water, Heritage and the Arts, Commonwealth of Australia, Canberra, Australia.

Crowl, T. A.; Townsend, C. R.; McIntosh, A. R., 1992: The impact of introduced brown and rainbow trout on native fish: the case of Australasia. Rev. Fish Biol. Fish **2,** 217–241.

De Winton, M.; Dugdale, T.; Clayton, J., 2003: Coarse fish: the demise of plants and malaise of lakes. Managing invasive freshwater Fish in New Zealand. Proceedings of a workshop hosted by the Department of Conservation, 10–12 May 2001, Hamilton. New Zealand Department of Conservation, Wellington.

Dugdale, T. M.; Hicks, B. J.; De Winton, M.; Taumopeau, A., 2006: Fish exclosures versus intensive fishing to restore charophytes in a shallow New Zealand lake. Aquat. Cons. Mar. Freshw. Ecosys. **16,** 193–202.

Goldsmith, R. J., 2004: Impacts of European perch *(Perca fluviatilis*) introduction on native common bully (*Gobiomorphus cotidianus*). PhD thesis, University of Canterbury, New Zealand.

Graynoth, E.; Bennet, E.; Pollard, J. C., 1986: Diet of landlocked sockeye salmon (*Oncorhyncus nerka*) and trout in the Waitaki lakes, New Zealand. N. Z. J. Mar. Freshw. Res. **20,** 537–549.

Hammond, T., 2009: Risk assessment guidelines for aquatic invasive species in North American inland waters. Aliens: the Invasive Species Bulletin. Newsletter of the IUCN ⁄ SSC Invasive Species Specialist Group. 28.

Hanchet, S. M., 1990: The effects of koi carp on New Zealand's aquatic ecosystems. Fisheries Environmental Report No.117, New Zealand Ministry of Agriculture and Fisheries, Fisheries Research Division, Rotorua.

Hicks, B. J., 2003: Biology and potential impacts of rudd (*Scardinius erythrophthalmus* L.*)* in New Zealand. In: Managing invasive freshwater fish in New Zealand. Proceedings of a workshop hosted by Department of Conservation, 10–12 May 2001, Hamilton. Munro, R. (Ed.) Department of Conservation, Wellington, pp. 49–58.

Huryn, A. D., 1996: An appraisal of the Allan paradox in a New Zealand trout stream. Limn. Ocean. **41,** 243–252.

James, G. D.; Unwin, M. J., 1996: Diet of Chinook salmon *(Oncorhynchus tshawytscha)* in Canterbury coastal waters, New Zealand. N. Z. J. Mar. Freshw. Res. **30,** 69–78.

Kolar, C., 2004: Risk assessment and screening for potentially invasive fishes. N. Z. J. Mar. Freshw. Res. **38,** 391–397.

Kolar, C. S.; Lodge, D. M., 2001: Progress in invasion biology: predicting invaders. Trends Ecol. Evol. **16,** 199–204.

Kolar, C. S.; Lodge, D. M., 2002: Ecological predictions and risk assessment for alien fishes in North America. Science **298,** 1233–1236.

Lake, M. D.; Hicks, B. J.; Wells, R. D. S.; Dugdale, T. M., 2002: Consumption of submerged aquatic macrophytes by rudd (*Scardinius erythrophthalmus* L.) in New Zealand. Hydrobiologia **470,** 13–22.

Leprieur, F.; Beauchard, O.; Blanchet, S.; Oberdof, T.; Brosse, S., 2008: Fish invasions in the worlds river systems: when natural processes are blurred by human activities. PLoS Biol. **6,** 0404–0410.

Levine, J. M.; Vila, M.; D'Antonio, C. M.; Dukes, J. S.; Grigulis, K.; Lavorel, S., 2003: Mechanisms underlying the impacts of exotic plant invasions. Proc. Roy. Soc. London, Series B, **270,** 775–781.

Li, H. W.; Moyle, P. B., 1981: Ecological analysis of species introductions into aquatic systems. Trans. Amer. Fish. Soc. **110,** 772–782.

Ludgate, B. G.; Closs, G. P., 2003: Responses of fish communities to sustained removals of perch (*Perca fluviatilis*) Science for Conservation **210**, New Zealand Department of Conservation, Wellington.

Marchetti, M. P.; Moyle, P. B.; Levine, R., 2004a: Invasive species profiling? Exploring the characteristics of non-native fishes across invasion stages in California Freshw. Biol. **49,** 646–661.

Marchetti, M. P.; Moyle, P. B.; Levine, R., 2004b: Alien fishes in California watershed: characteristics of successful and failed invaders. Ecol. Appl. **14,** 587–596.

McDowall, R. M., 1968: The proposed introduction of the largemouth bass *Micropterus salmoides* (Lacepidae) into New Zealand. N. Z. J. Mar. Freshw. Res. **2,** 149–161.
McDowall, R. M., 1984a: Exotic fishes: the New Zealand experience. In: Distribution, biology and management of exotic fishes. W. R. Courtenay and J. R. Stauffer (Eds), Johns Hopkins University Press, Baltimore and London, pp. 200–214.
McDowall, R. M., 1984b: Trout in New Zealand waters. The Wetland Press, Wellington.
McDowall, R. M., 1987: Impacts of exotic fishes on the native fauna. In: Inland waters of New Zealand. A. B. Viner (Ed). DSIR Bull. **241**, Science Information Publishing Center, Wellington, pp. 333–348.
McDowall, R. M., 1990: New Zealand Freshwater Fishes – a natural history and guide. Heinemann Reed MAF Publishing Group, Wellington.
McDowall, R. M., 2003: Impacts of introduced salmonids on native galaxiids in New Zealand upland streams: a new look at an old problem. Trans Amer. Fish. Soc. **132,** 229–238.
McDowall, R. M., 2004: Shoot first, and then ask questions: a look at aquarium fish imports and invasiveness in New Zealand. N. Z. J. Mar. Freshw. Res. **38,** 503–510.
McDowall, R. M., 2006: Crying wolf, crying foul, or crying shame: alien salmonids and a biodiversity crisis in the southern cool-temperate galaxioid fishes? Rev. Fish Biol. Fish. **16,** 233–422.
McDowall, R. M.; Richardson, J., 1983: The New Zealand freshwater fish survey database: guide to input and output. New Zealand Ministry of Agriculture and Fisheries, Christ Church, New Zealand.
McIntosh, A. R., 2000: Habitat and size-related variations in exotic trout impacts on native galaxiid fishes in New Zealand streams. Can. J. Fish. Aquat. Sci. **57,** 2140–2151.
McIntosh, A. R.; Townsend, C. R., 1995: Contrasting predation risks presented by introduced brown trout and native common river galaxias in New Zealand streams. Can. J. Fish. Aquat. Sci. **52,** 1821–1833.
Miller, D. J., 1989: Introductions and extinctions of fish in the African Great Lakes. Trends Ecol. Evol. **4,** 56–59.
Moyle, P. B.; Light, T., 1996: Biological invasions of freshwater: empirical rules and assembly theory. Biol. Cons. **78,** 149–161.
Neilson, K.; Kelleher, R.; Barnes, G.; Speirs, D.; Kelly, J., 2004: Use of fine-mesh monofilament gill nets for the removal of rudd (*Scardinius erythrophthalmus*) from a small lake complex in Waikato, New Zealand. N. Z. J. Mar. Freshw. Res. **38,** 525–539.
Parker, I. M.; Simberloff, D.; Lonsdale, W. M.; Goodell, K.; Wonham, M.; Kareiva, P. M.; Williamson, M. H.; Von Holle, B.; Moyle, P. B.; Byers, J. E.; Goldwasser, L., 1999: Impact: towards a framework for understanding the ecological effect of invaders. Biol. Invas. **1,** 3–19.
Pheloung, P. C.; Williams, P. A.; Halloy, S. R., 1999: A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. J. Environ. Manag. **57,** 239–251.
Ricciardi, A.; Cohen, J., 2006: The invasiveness of an introduced species does not predict its impact. Biol. Invas. **9,** 309–315.
Ricciardi, A.; Rasmussen, J. B., 1998: Predicting the identity and impact of future biological invaders: a priority for aquatic resource management. Can. J. Fish. Aquat. Sci. **55,** 1759–1765.
Rowe, D. K., 2003: Balancing native fish diversity, exotic fish impacts and angling in New Zealand, North Island dune lakes. In: Aquatic Protected Areas – what works best and how do we know. Proceedings of the World Congress on Aquatic Protected Areas, Cairns, Australia, August 2002. J. Beumer, A. Grant and D. C. Smith (Eds). Australian Society for Fish Biology, Brisbane, Australia, pp. 96–102.
Rowe, D. K., 2004: Potential effects of tench (Tinca tinca) in New Zealand freshwater ecosystems. NIWA Client Report HAM2004-005. National Institute of Water and Atmospheric Research Ltd., Hamilton.
Rowe, D. K., 2007: Exotic fish introductions and the decline of water clarity in small North Island, New Zealand lakes: a multi-species problem. Hydrobiologia **583,** 345–358.
Rowe, D. K., 2010: An assessment of the potential uses and impacts of the filter-feeding fish, silver carp (Hypophthalmichthys molitrix) in New Zealand waters. NIWA Client Report HAM2010-002: National Institute of Water and Atmospheric Research Ltd., Hamilton.
Rowe, D. K.; Champion, P. D., 1994: Biomanipulation of plants and fish to restore Lake Parkinson: a case study and its implications. In: Restoration of aquatic habitats. K. J. Collier (Ed). Department of Conservation, Wellington, pp. 53–65.
Rowe, D. K.; Chisnall, B. L., 1997: Environmental factors associated with the decline of dwarf inanga (*Galaxias gracilis*, McDowall) in New Zealand dune lakes. Aquat. Cons. Mar. Freshw. Ecosys. **7,** 277–286.
Rowe, D. K.; Graynoth, E., 2002: Lake managers handbook: fish in New Zealand lakes. Ministry for the Environment, Wellington.
Rowe, D. K.; Schipper, C. M., 1985: An assessment of the impact of grass carp in New Zealand waters. Fisheries Environmental Report No. 58. New Zealand Ministry of Agriculture and Fisheries, Fisheries Research Division, Rotorua.
Rowe, D. K.; Smith, J. P., 2002: The role of exotic fish in the loss of macrophytes and increased turbidity of Lake Wainamu, Auckland. NIWA Client Report ARC02286.
Rowe, D. K.; Smith, J. P., 2003: Exotic fish in ARC lakes: implications for water quality decline and the identification of restoration options. NIWA Client Report HAM2003-076. National Institute of Water and Atmospheric Research Ltd., Hamilton.
Rowe, D. K.; Smith, J. P.; Baker, C., 2007: Agonistic interactions between *Gambusia affinis* and *Galaxias maculatus*: implications for whitebait fisheries in New Zealand rivers. J. Appl. Ichthyol. **23,** 668–674.
Rowe, D. K.; Moore, A.; Georgetti, A.; Maclean, C.; Grace, P.; Corfield, J.; Wadhwa, S.; Cooke, J., 2008: Review of the impacts of gambusia, redfin perch, tench, roach, yellowfin goby and streaked goby in Australia. NIWA Client Report No AUS2008-001. National Institute of Water and Atmospheric Research Ltd., Hamilton.
Ruesink, J. L., 2005: Global analysis of factors affecting the outcomes of freshwater fish introductions. Cons. Biol. **19,** 1883–1893.
Schallenberg, M.; Sorrell, B., 2009: Regime shifts between clear and turbid water in New Zealand lakes: environmental correlates and implications for management and restoration. N. Z. J. Mar. Freshw. Res. **43,** 701–712.
Simberloff, D., 2009: The role of propagule pressure in biological invasions. Ann Rev. Ecol. Syst. **40,** 81–102.
Smith, K. F.; Lester, P. J., 2006: Cyanobacterial blooms appear to be driven by top-down rather than bottom-up effects in the Lower Karori Reservoir (Wellington, New Zealand). N. Z. J. Mar. Freshw. Res. **40,** 53–63.
Taylor, J. N.; Courtenay, W. R., Jr; McCann, J. A., 1984: Known impacts of exotic fish in the continental United States. In: Distribution, biology and management of exotic fishes. W. R. Courtenay Jr and J. R. Stauffer (Eds). Johns Hopkins Press, Baltimore, MD, pp. 322–373.
Townsend, C. R.; Crowl, T. A., 1991: Fragmented population structure in native New Zealand fish: an effect of introduced brown trout? Oikos **61,** 347–354.
Townsend, C. R.; Winterbourn, M. J., 1992: Assessment of the environmental risk posed by an exotic fish: the proposed introduction of channel catfish (*Ictalurus punctatus*) to New Zealand. Cons. Biol. **6,** 273–282.
Webb, A. C., 2006: Risk assessment screening for potentially invasive freshwater fishes within the wet tropics bioregion: a review of assessment approaches, identification of knowledge gaps and future recommendations. Report No 06/26. Australian Centre for Tropical Freshwater Research, James Cook University, Townsville.

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