Natural Heritage Trust
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A Commonwealth Government Initiative

Australian Government
Bureau of Rural Sciences

Risk assessment model for the import and keeping of exotic freshwater and estuarine finfish

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June 2004

A report produced by the Bureau of Rural Sciences for The Department of Environment and Heritage

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Foreword

Exotic fish introduced into Australia can establish wild pest populations that cause environmental and economic harm. Predatory fish have the potential to cause extinctions of native fish species or reduce their range and abundance. Exotic fish can also compete with native fish for food and other resources. Other harm potentially caused by exotic fish includes altering the habitat of native species, spreading diseases and hybridising with native fish.

There is a risk that new exotic fish species could establish as wild pests in Australia. If such fish escaped or were illegally released into a favourable environment, they could start to breed in the wild and spread to new locations. Once they are widespread, eradication becomes virtually impossible.

Not all exotic fish species pose the same level of threat for establishing a wild pest population. This report addresses the question of whether it is possible to distinguish between species that pose a high risk and those that pose a lower risk. Based on a review of world scientific literature and an analysis of past introductions of exotic fish to Australia, it concludes that there is a suite of factors that separates high and low-risk species. This information is used to construct a scientifically based risk assessment model to evaluate the risk that an exotic fish species released into the wild could establish a wild population.

The Bureau of Rural Sciences produced this report for The Department of Environment and Heritage with funding from the Natural Heritage Trust. The report provides information to assist the Commonwealth and State and Territory Governments assess the risks posed by the import and keeping of exotic fish.

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Summary

Around 50% of reported exotic fish introductions have resulted in new populations establishing.

On average, around 50% of reported exotic fish introductions have resulted in new populations establishing although this figure varies between fish taxa and in different locations. This figure may overestimate the true success rate because successful introductions are more likely to be reported.

Assessing invasion risk relies on identifying factors that are linked to the probability of successful establishment if a new fish species were introduced and released in Australia. There is a considerable scientific literature on the ecological theory of fish invasions, proposing a suite of factors that may influence whether or not they establish in new environments.

Establishment risk

There are five key factors for which there is strong evidence of a correlation with establishment success. These should be considered key factors when the risk that exotic fishes could establish here is assessed:

The release of large numbers of fish at different times and places enhances the chance of successful establishment.

1. *Number of release events:*

The release of large numbers of fish at different times and places enhances the chance of successful establishment. Small populations are more susceptible to extinction from predation, reduced breeding success, poorer hunting success or increased inter-specific competition. Chance events such as droughts and floods are also likely to drive small populations to extinction. Small populations may also lose genetic variability that may reduce the probability of long-term survival. The minimum viable population size for successful invasion is not known for most species.

All species for which more than ten introduction events have been recorded have established at least one exotic population.

An analysis of worldwide fish introductions indicates a strong correlation between the number of times a fish species is introduced and the number of exotic populations it establishes. All species for which more than ten introduction events have been recorded have established at least one exotic population. Thus it appears likely that most fish species can establish exotic populations if sufficient releases are made into suitable environments. This risk can be reduced by restricting which species are kept in Australia, the number of collections holding a species, the number of individuals held in each collection, the security conditions for keeping species, and by educating people about the risks of releasing exotic fish into waterways. Any changes to policy or management for exotic species that reduce restrictions on where exotic species can be held, or the numbers of species held, are likely to increase the risk that more exotic fish species will establish wild populations in Australia.

2. *Climate match*:

Exotic fish have a greater chance of establishing if they are introduced to an area with a climate that closely matches that of their original range.

Exotic fish have a greater chance of establishing if they are introduced to an area with a climate that closely matches that of their original range. Species that have a large overseas range over several climatic zones are predicted to be strong future invaders. The suitability of Australian environments for the establishment of a species can be quantified on a broad scale by measuring the climate match between Australia and the overseas geographic range of a species. Climate matching models generate maps of probability of successful establishment in Australia of a species introduced from any part of the world. Successfully introduced species in Australia have a greater area of climatically matched habitat than species that were released in Australia but failed to establish. Climatic matching only sets the broad parameters for determining if an area is suitable for an exotic fish to establish. Many factors, such as unsuitable water chemistry or flow dynamics, the absence of suitable spawning habitats or food, or the presence of competitors, predators or diseases, might prevent an exotic fish from establishing in a climatically matched area.

3. *History of establishing exotic populations elsewhere:*

A history of establishing exotic populations elsewhere is a significant predictor of establishment success for exotic fish introduced to Australia.

A history of establishing exotic populations may indicate that a species has attributes that increase the risk of it establishing in other areas. A history of establishing exotic populations elsewhere is a significant predictor of establishment success for exotic fish introduced to Australia and to the Great Lakes of North America. However, many species that are potential exotics have not been transported to and released in new environments, so they have not had the opportunity to demonstrate their establishment potential. Hence, caution should be applied when using a history of establishment elsewhere to predict a species' establishment potential in Australia if the species being assessed has little or no history of previous introductions.

4. *Overseas geographic range size:*

Species that have a wide geographic range are more likely to establish exotic populations than species with restricted ranges.

Species that have a wide geographic range are more likely to establish exotic populations than species with restricted ranges. A wide geographic range could indicate flexible or generalist species, or good dispersers, and hence species that are more likely to invade successfully. A comparison of the 31 successfully established species of exotic fish in Australia with the 19 species that were introduced but failed to establish indicates that the successful species have larger overseas range sizes.

5. Taxonomic group:

Both family and genus are significantly correlated with introduction success rate for exotic fish species introduced around the world. The seven most successful families are Gobiidae, Cobitidae, Poeciliidae, Clupeidae, Loricariidae, Atherinidae and Osteoglossidae. A precautionary approach may be advisable for fish that have little or no introduction history, and without relatives with an introduction history.

Both family and genus are significantly correlated with introduction success rate for exotic fish species introduced around the world.

There are many additional factors listed in the literature that are hypothesized to enhance the probability of establishment but for which scientific supporting evidence is lacking or equivocal. Rigorous designed experiments are required to confirm or reject the potential role of these factors which include:

Fish with:

- high fecundity (average number of females produced by females surviving to reproductive age) and associated attributes (rapid growth rates and early sexual maturity, large clutch size, frequent spawnings and extended spawning period, high breeding frequency, short gestation and opportunistic or aseasonal breeding)
- broad environmental tolerances for temperature, acidity, oxygen levels, and hydrological regimes
- high genotypic and phenotypic variability and behavioural flexibility in diet, behaviour and nesting habits in different environments may increase establishment success because high variability increases the potential for rapid adaptive radiation
- good dispersal abilities
- broad and/or flexible diets (dietary generalists)
- live in human-disturbed habitats – human commensalism
- ability to give birth to live young or exhibit parental care of eggs or young
- aggressive behaviour and territoriality
- gregariousness
- larger body size
- fit, healthy young animals with low parasite or disease loads
- fertilised female able to colonise alone.

There are many additional factors listed in the literature that are hypothesized to enhance the probability of establishment but for which scientific supporting evidence is lacking or equivocal.

And also:

- care following release, such as sheltering or feeding the newly introduced fish
- habitat disturbance in the release site
- an absence or low occurrence of natural enemies such as predators, competitors, parasites or diseases in the release site
- wild caught animals are more successful at establishing exotic populations than captive-reared animals.

Unfortunately many of the statistical tests conducted to look for factors that may be correlated with establishment success have lacked power.

Successfully introduced species differ widely from one another in many attributes including spawning habits, degree of parental care, adult size, feeding habits, and native habitat. Unfortunately, many of the statistical tests conducted to look for factors that may be correlated with establishment success have lacked power, because sample sizes are often small and because fish species that have been introduced do not necessarily evenly represent the attributes that ecologists want to test. Hence, a significant effect on establishment success will often only be demonstrated for factors that have a fairly major and consistent effect, such as climate match and introduction effort. Where no significant effect has been found for a factor, such as for diet and human commensalism, this does not mean that it does not influence establishment success. Expert opinion, published in the scientific literature, suggests that such factors may well be potentially important and, thus perhaps they should be considered in the qualitative components of risk assessments.

Scientific theory and knowledge are still inadequate for making certain predictions about the invasive capability of individual species.

Scientific theory and knowledge are still inadequate for making certain predictions about the invasive capability of individual species. This uncertainty has led many experts to question whether it is even feasible to try to reliably predict whether exotic animals could establish in a new country. However, predictions of invasion risk by exotic species, based on fairly simple risk assessment models, which include such factors as climate matching, overseas range size, and past invasion successes by the species or its close relatives, will allow predictions to be made at low cost to guide management policies. Such simple approaches may overestimate the probability of establishment success, but the low cost of using them to assess risk will enable large numbers of potential invaders to be screened, whereas more complicated approaches that require intensive, long-term and expensive study will make the assessment of many species prohibitively expensive.

Impact risk

Predictions of invasion risk by exotic species, based on fairly simple risk assessment models, allow predictions to be made at low cost to guide management policies.

The potential impacts of exotic fish can be classified into three main categories:

1. *Environmental impacts* – including reduced biodiversity, reduced or eliminated endangered species and ecosystem destabilisation.
2. *Economic impacts* – including reduced agricultural or fisheries productivity or increased production costs, trade effects and damage control costs.
3. *Social and political impacts* – including aesthetic damage, consumer concerns and political repercussions.

Unfortunately reliable knowledge about impacts is sparse for most exotic finfish both in Australia and overseas.

Many of the impacts attributed to exotic fish are correlative or anecdotal. A demonstration of environmental impact requires verification of a causal relationship between changes in a native population, a previously introduced exotic population, or in an aquatic community, and the presence of the exotic fish. Unfortunately reliable knowledge about impacts is sparse for most exotic finfish, both in Australia and overseas, for two main reasons. Firstly there has been limited research and in particular there are usually scarce preinvasion data sets. Secondly, introductions of exotic finfish have often coincided with other changes to freshwater and estuarine habitats. This means impacts due to exotic fish are confounded with impacts due to other factors such as changed water flows and temperature regimes due to dams or irrigation or to reduced water quality due to pollution. The combined effects of introduced species and human-caused environmental changes may cause rapid and unpredictable changes in fish assemblages

Introductions of exotic finfish have often coincided with other changes to freshwater and estuarine habitats.

It is not possible to estimate a reliable figure for the percentage of exotic fish that become pests because few reliable data on fish impacts are available and hence impacts due to exotic fish are largely under-reported in the scientific literature. A review of published literature on fish introductions around the world published in 1991 found 77% of the 31 studies reviewed reported a decline in native fish numbers following the fish introductions. Most changes due to exotic fish are subtle effects such as local extirpations, behavioural and evolutionary changes of native species, habitat and environment changes, food web alterations, and transmission of pathogens. Such effects are rarely investigated in detail.

Competition and predation by exotic fish both have the potential to be highly detrimental to native species.

Competition and predation by exotic fish both have the potential to be highly detrimental to native species but scientific knowledge is currently inadequate to allow reliable predictions about which exotic species will have the worst impacts due to these factors when they are introduced to new environments. Piscivores are be more likely to alter invaded communities than fish from other dietary groups and are responsible for most recorded cases of introduced fish causing extinctions of native fish. Exotic fish may also have detrimental effects on recipient ecosystems when they alter the habitat of native species, for example by destroying or modifying aquatic vegetation. Diseases spread from exotic fish to native fish may have huge ecological consequences. When exotic fish hybridise with native fish, and produce fertile offspring, this corrupts the gene pool of the native fish and hence may pose a threat to their survival.

Piscivores are be more likely to alter invaded communities than fish from other dietary groups and are responsible for most recorded cases of introduced fish causing extinctions of native fish.

Simple predictions can be made by assuming that invaders will cause significant impacts in a new area they have established if they have already done so in other regions. However, since Australian aquatic systems are inherently different from overseas ones, there are limits to the extent to which conclusions about impacts drawn from overseas studies can be extrapolated to Australian conditions. Further, a species' history of impacts elsewhere is not an infallible guide to its potential impact in Australia. There are many examples in the scientific literature of species that have developed new behaviour and new dietary preferences when introduced to new environments and hence had impacts that could not have been predicted from their history. Species that have little harmful effect in their native (or previously introduced) range may have devastating effects when introduced to a new country. Some species have not yet been introduced to new areas, so their pest potential is yet to be demonstrated.

Many species have developed new behaviour when introduced to new environments and hence had impacts that could not have been predicted from their history.

Species that spread rapidly from their initial place of establishment are likely to be harder to eradicate, contain or control, and are more likely to become widespread and to be considered to be pests, than species with a slow rate of spread.

Identifying species that can potentially cause ecological harm is inevitably a subjective process.

Defining harmful species and identifying species that cause or can potentially cause ecological harm is inevitably a subjective process and it is not possible to make reliable decisions about which species are safe to import because they pose a low risk of harm. There is insufficient reliable knowledge of the factors correlated with impacts of exotic fish to make the development of a quantitative model feasible for assessing the risks of impact for new species of exotic fish in Australia. Nonetheless, the review of factors associated with adverse impacts above indicates that an increased risk is associated with fish that:

- have adverse impacts elsewhere
- have close relatives with similar behavioural and ecological strategies that cause adverse impacts elsewhere
- are generalist feeders
- are piscivorous
- destroy or modify aquatic vegetation or stir up sediments to increase turbidity
- have the the potential to cause physical injury
- harbour or transmit diseases or parasites that are present in Australia
- have close relatives among Australia's endemic fish
- are known to have spread rapidly following their release into new environments.

This list could be used as a checklist to make a qualitative assessment of the threat of impacts posed by the establishment of new exotic fish species in Australia. However, an absence of these factors cannot be taken to indicate that there is a low risk of harm.

The risk of new exotic fish species establishing in Australia can be expected to increase as the number of people keeping exotic fish increases.

The risk of new exotic fish species establishing in Australia can be expected to increase as the number of people keeping exotic fish increases and the numbers of different fish species kept in collections increases. This is because, as more people keep fish, the number of escapes and releases of new fish species is also likely to increase, and establishment of exotic fish is closely correlated with the number of release events. This risk can be reduced by restricting the import and keeping of fish species that:

- have a good climate match to Australia
- have a history of establishing exotic populations elsewhere
- have a large overseas geographic range size
- are in a genus or family that has a high introduction success overseas.

A new model presented in this report provides a simple quantitative method for ranking fish.

A new model presented in this report provides a simple quantitative method for ranking fish against these factors. All the data required to assess new fish species using the model are available on the internet in Fishbase. This model was developed from an assessment of the attributes of exotic fish that have been from an assessment of the attributes of exotic fish that have been introduced in Australia, using five factors that discriminated between those fish that successfully established and those that were released but failed to establish wild populations. The model ranks the risk of establishment for a fish at five possible levels, ranging from very low to extreme. In this model 87% of the exotic fish that have established in Australia are ranked in the high–extreme risk range and 72% of the exotic fish that failed to establish are ranked in the very low–moderate risk range. Five fish that have so far failed to establish are ranked as high or very high risk in the model (rosy barb *Puntius conchonius*; firemouth cichlid *Thorichtys meeki*; blue tilapia *Oreochromis aureus*; wami tilapia *Oreochromis urolepis*; Atlantic salmon *Salmo salar*) and it is possible that these fish may establish in the future if there are more releases. Only one fish that is given a low establishment risk in the model has established (Victoria Burton’s haplochromine *Haplochromis burtoni*).

Fishbase (2004) lists 27 species of exotic fish that have been reported by one or more countries as having adverse ecological impacts. These species all score in the high–extreme establishment risk range for Australia, with the single exception of the bighead carp *Aristichthys nobilis* which scores a moderate risk.

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Introduction

The model and discussion in this report relates to the potential introduction of finfish into freshwater and brackish habitats. It is not intended to apply to marine finfish introduced to Australia via ballast water. Strategies for assessing and responding to the risks posed by finfish introduced in ballast water are discussed by Ricciardi and Rasmussen (1998).

1. Threat to biodiversity

The introduction and spread of exotic fish are a major threat to biodiversity, particularly through the endangerment and extinction of native fish, invertebrates and amphibians (Moyle and Williams 1990; Arthington 1991; Jenkins 1996; Kottelat and Whitten 1996; Arthington and McKenzie 1997; Ricciardi and Rasmussen 1998; Kailola 2000; Ricciardi et al. 2000; Elvira 2001; Hayes and Sliwa 2003). Effects on plants are less well understood but can also be significant. All introduced species have some impact on the environment. The impacts may occur at the level of individual organisms, the gene pool, the population, the community or ecosystem processes (Parker et al. 1999). Ricciardi and MacIsaac (2000) consider that lakes and estuaries are among the ecosystems most susceptible to invasion.

The number of exotic fish reported as having established self-sustaining populations in Australian waters is increasing at an accelerating rate (Lintermans in prep. 2004; Table 1). Even greater increases are being experienced in some other countries. For example, in Florida, the number of exotic fish taxa reported or established increased from 19 in 1970 to 91 in 1998 (Nico and Fuller 1999). The majority of recently established fish species are aquarium fish, particularly tropical species in Australia.

Ricciardi and Rasmussen (1999) used an exponential decay model incorporating current extinction rates to predict future extinction rates (expressed as per cent loss of species per decade) of endemic fauna in North America. These authors predict an annual extinction rate for freshwater finfish of 2.4%, which exceeds the predicted extinction rates for other vertebrate taxa (birds 0.7%, reptiles 0.7%, land mammals 0.7% and marine mammals 1.1%), with the exception of amphibians (3.0%). Ricciardi and Rasmussen (1999) predict even higher extinction rates for other freshwater fauna: crayfish (3.9%); mussels (6.4%); and gastropods (2.6%). The projected extinction rates for freshwater fauna are about five times those for terrestrial fauna and three times the rate for coastal marine mammals. Ricciardi and Rasmussen (1999) link the high extinction rates for freshwater fauna to interactions with increasing numbers of exotic species, as well as habitat deterioration caused by sediment loading, organic pollution from land-use activities, toxic chemical pollution, stream fragmentation and flow regulation from dams, channelisation and dredging. They suggest that freshwater fauna on other continents are probably similarly threatened.

Table 1. Increases in the number of exotic fish species established in Australia.

Date	Number of species	Families represented	Source
1967	9	Salmonidae (2) Percidae (1) Cyprinidae (5) Poeciliidae (1)	Weatherley and Lake (1967)
1997	19	Salmonidae (3) Percidae (1) Cyprinidae (4) Poeciliidae (6) Cichlidae (3) Cobitidae (1) Gobidae (1)	Arthington and McKenzie (1997)
2004	31*	Salmonidae (3) Percidae (1) Cyprinidae (5) Poeciliidae (6) Cichlidae (10*) Cobitidae (1) Gobidae (4) Belotiidae (1)	Lintermans in prep. (2004) and Lintermans pers. comm. (2004)

* Lintermans (in prep. 2004) additionally reported an unidentified hybrid cichlid.

Import and use of exotic fish

Freshwater angling is a major recreational industry in Australia. Recreational fishing has led to many fish introductions around the world and it also supports many aquaculture, fish farming and stocking operations that result in exotic fish introductions (Welcomme 1988; Arthington and McKenzie 1997; Elvira 2001). Exotic species used to feed cultivated stocks have also been known to escape (Arthington and McKenzie 1997). Exotic species are also used as live bait by recreational fishers and this can lead to establishment of exotic populations (Elvira 2001). Exotic fish, including weatherloach *Misgurnus anguillicaudatus*, European carp *Cyprinus carpio*, goldfish *Carassius auratus*, redfin perch *Perca fluviatilis* and Mozambique tilapia *Oreochromis mossambicus*, are used as live bait in Australia and this enhances their dispersal (Brumley 1991; Kailola 2000; Raadik 2001; Lintermans in prep. 2004).

Thousands of exotic fish are imported into Australia each year for the aquarium fish trade and between 1972 and 1978 up to15 million fish were imported each year (Kailola 1990, 2000). Although import numbers have since declined, the number of exotic fish bred in Australia for the aquarium trade has increased (Arthington and Mckenzie 1997). There is also 'backyard' breeding of non-approved aquarium fish – either of smuggled imports or previously approved taxa and these fish are widely traded (Kailola 1990). All the poeciliids (except for the mosquito fish *Gambusia holbrooki* that was introduced for biocontrol), cichlids, the cobitid and the belotiid plus two of the cyprinids currently established in Australian waters were originally introduced as aquarium fish (Lintermans in prep. 2004). Many of these species have enormous potential for spread.

It is likely that the large majority of exotic freshwater fish introduced into Australian waters in the future will be sourced from the aquarium trade although some may come from ballast water or aquaculture. Kailola (2000) bases this prediction on:

1. The number of recently recorded aquarium fish species in Australia.
2. A comparison with the United States where Nico and Fuller (1999) found that the number of species introduced since 1951 is almost triple the number introduced there in the 200 years before 1951 and that one of the major reasons for the increase has been the ‘tremendous growth of the ornamental fish industry’. In the southern United States, the numbers of introduced foreign fish are closely correlated with number and size of ornamental fish farm operations and in Florida the cumulative number of exotic fish taxa reported or established has increased from 19 in 1970 to 91 in 1998 (Nico and Fuller 1999).
3. The high number of exotic freshwater taxa imported into Australia for the aquarium fish trade over the past 40 years. Andrews (1990) reported estimates of 14% of homes in the United Kingdom and 8% of homes in the U.S.A. have aquarium fish and Kailola (2000) suggests Australia may lie between these levels.

According to Elvira (2001), many introductions of exotic fish have resulted from accidental release or private initiative, and the relatively large number of such introductions worldwide illustrates the difficulty of containing exotic fish within limited environments such as ponds or aquaria. Release of aquarium fish is the main pathway for exotic fish establishment in Australia with 19 of the last 21 fish species that have established originating from the aquarium trade (Lintermans in prep. 2004). According to Kailola (2000), releases of aquarium fish are very common in metropolitan areas and in towns supporting short-term residents (such as students and contract workers). For example, there are reports of populations of exotic aquarium fish in natural water bodies near military bases in central and Western Australia. New exotic fish populations come from: disposal of aquarium fish into impoundments and rivers; escape of fish from outdoor ornamental ponds (especially during flooding);and deliberate (and unauthorised) releases to enhance recreational fisheries (Kailola 2000). Basically people are often reluctant to kill unwanted aquarium fish and prefer to release them into a ‘suitable’ environment. There is often no practical way to prevent such releases (Arthington and Bluhdorn 1995; Kailola 2000). Once an exotic fish species has established, it is usually not possible to eradicate or even contain it and attempts would be prohibitively expensive unless the population was very small and confined (Kailola 2000). Therefore, restricting the import and keeping of high-risk species is critically important.

Positive identification of exotic fish species is an essential pre-requisite for determining their status and successfully managing their import and keeping (Nico and Fuller 1999). Unfortunately there is often confusion or uncertainty with the identification of exotic fish, including some of those that are believed to be established in Australia (Kailola pers. comm. 2004). Examples of particularly problematic taxa are the tilapias, poeciliids and many tropical fish including loricariid catfishes, piranhas and pacus (Nico and Fuller 1999). Problems arise because of hybridisation and because of poor state of knowledge about systematics and taxonomy of certain fish groups. It is highly desirable for voucher specimens to be taken and made available so questions about identification can be resolved.

2. Developing reliable predictive risk assessment approaches

Some ecologists doubt that it is possible to build accurate models to predict the outcomes of exotic finfish introductions because there has been so little progress in developing generalisations about the factors affecting the establishment and impacts of introduced species (Ricciardi and Rasmussen 1998; Williamson 1999; Kolar and Lodge 2001). These ecologists often consider the consequences of an introduction are largely dependent on individual circumstances (such as timing, biotic and abiotic components of the invaded habitat, and numbers and condition of introduced fish) and on stochastic events, all of which can make outcomes highly unpredictable. Hence many ecologists claim that predicting the outcome of introductions of exotic invaders will require focused study on each individual potential invader and the recipient habitat (Lodge 1993a,b). Such approaches are costly because they require long-term research. Daehler and Strong (1993), however, suggest the improved predictive power from such expensive studies is questionable because of the poor predictive ability of community ecology even for well-studied systems.

Other ecologists believe that simple models, if based on reliable data, can provide valuable information on invasion threats in the form of robust generalisations (Ricciardi and Rasmussen 1998; Ricciardi 2003). Kolar and Lodge (2002) looking at fish invasions in North America, Bomford (2003) looking at potential terrestrial vertebrate invasions, and Daehler and Strong (1993) looking at potential plant invasions, described general factors which do not require expensive long-term research and can be used for predictive risk assessments. Predictions from these approaches may not always give complete accuracy regarding invasion success and consequences, but the low cost of generating these predictions (compared to the potentially high cost of losing endemic native communities and species to exotics) may make them the best available for making decisions on the import and keeping of exotic species.

According to Moyle and Light (1996b) there are numerous documented instances where invading fish species have established and seem to have become integrated into the local biota without causing extinctions of native species. Yet there are also instances where a single species introduction has resulted in the extinction of hundreds of endemic species, such as the introduction of Nile perch *Lates nilotica* to Lake Victoria, Africa, which resulted in the extirpation of over 200 haplochromine cichlids (Welcomme 1988). Hence Moyle and Light (1996b) consider our ability to predict the effects of biotic invasions into aquatic systems is limited, and often effects are unexpected and negative. Moyle and Light (1996b) reviewed community assembly theory in the light of a series of case histories of freshwater finfish invasions. Community assembly theory looks for patterns in dynamic ecological communities which are built by a continuous process of sequential invasions and extinctions – these rules or patterns underlying this process could assist with predicting outcomes of species invasions. Moyle and Light (1996b) draw up some general rules from their analysis, but several of these are controversial and have been challenged by other ecologists. For example, Ricciardi and MacIsaac (2000) point out that some invasions are assisted by previous invasions, in contrast to the theory of biotic resistance, which predicts that communities become more resistant to invasion as they accumulate more species (Case 1991; Moyle and Light 1996a). According to Moyle and Light (1996b), 'predicting the likelihood of success of an invading species depends on detailed understanding of the characteristics of the invading species and of the system being invaded'. They say 'both are likely to be fairly idiosyncratic, making generalised theory difficult to apply'. They conclude the predictions of assembly theory 'appear to be of limited usefulness for predicting the outcomes of biological invasions' (see Section 1.2.2ii for further discussion). Instead, Moyle and Light (1996b) suggest the nature of the environment being invaded (climate match, hydrological conditions, water chemistry and patterns or predictability in fluctuations in these) and biological characteristics of the invader are more likely to determine the outcomes of invasions. Moyle and Light (1996b) consider we are still far from being able to make reliable predictions about which fish introductions will be benign and which will have devastating consequences like Nile Perch. Despite this they consider the 'development of a predictive model is possible for aquatic systems' but say the complexity and poor predictive ability means that we cannot make reliable predictions.

One problem for creating reliable predictions is the time lag between initial introductions and detectable impact (Ricciardi 2003). Following introduction there is often an initial lag period corresponding to slow population growth and spread which may last years to decades. This may be due to several factors such as density-dependent effects of natural enemies (predators, competitors, diseases and parasites) and genetic selection (Shigesada and Kawasaki 1997; Ricciardi 2003). For example, the Nile perch was introduced to Lake Victoria in Africa in about 1954 but remained a minor component of the community until the 1980s when it underwent a population explosion and had detrimental effects on hundreds of endemic species of cichlids (Kaufman 1992). Similarly, the European carp probably established in Australia in the 1930s but did not start their rapid spread until the 1970s (Koehn et al. 2000).

According to Ricciardi et al. (2000), retrieving critical information about the spread, impact and control of invasive species is difficult because 'much of this information is buried in disciplinary journals from many different fields… or in obscure government documents and technical reports ("grey literature") that are not widely accessible'. Additional information is only known to ecologists who work on an exotic species in its country of origin (Townsend and Winterbourn 1992). The diffuse distribution and variable quality of this information makes it imperative that those who conduct risk assessments have adequate skills and resources to access it and the expertise and independence to impartially evaluate its significance. For example, an initial environmental impact assessment (EIA) conducted on the risks associated with introducing channel catfish *Ictalurus punctatus* to New Zealand for aquaculture failed to find evidence of potential adverse effects on New Zealand native species. This finding led to a permit being granted to import fertilised eggs from California and channel catfish were reared from these eggs under quarantine in New Zealand. Further information was then obtained from scientific experts working in the fish's natural range in North America. This new information revealed that where channel catfish had been introduced outside their natural range in California, native fish were rarely able to coexist with it (Townsend and Winterbourn 1992). The species also had significant impacts on natural ecosystems and was a major predator of trout, salmon and crayfish. An evaluation of this new evidence by an independent review team concluded that the introduction of channel catfish to New Zealand could lead to extinctions of some native species and disrupt aquatic ecosystems and could also detrimentally affect commercial, recreational and traditional fisheries. The review team considered the risks were unacceptable, and their recommendation was accepted and the fish in quarantine were destroyed. Townsend and Winterbourn (1992) concluded from these events that it is crucial that any assessment of exotic fish species proposed for import be reviewed by experts in the fish's country of origin. Experts with knowledge of the outcomes of any previous introductions of the species are particularly necessary. Townsend and Winterbourn (1992) also stressed the need for the process to be conducted by experts who are independent of vested interests in importation.

Risk assessments, no matter how objective the selection criteria, are dependent for accuracy and consistency on the skill and thoroughness of the assessor. One problem that can lead to bias is that literature reviews are often restricted to publications in English and global coverage is often neither complete nor uniform across continents (Hayes and Sliwa 2003). Further, even when it is possible to access non-English literature, knowledge about exotic species introductions and their impacts is uneven on a world scale, with more research being undertaken in North America and Western Europe than elsewhere.

A risk assessment model cannot determine whether or not an introduced exotic species will establish and if it does what impact it will have (Aquatic Nuisance Species Taskforce 1996). The best that can be achieved is to estimate the likelihood that a species will establish and estimate its potential to cause harm. Likewise, a risk assessment model cannot determine the acceptable risk level (Aquatic Nuisance Species Taskforce 1996). What risk, or how much risk is acceptable depends on how an agency perceives that risk. Risk levels are value judgments that are characterised by variables beyond the systematic evaluation of information.

There is always uncertainty in risk assessments and these can be divided into three types (Aquatic Nuisance Species Taskforce 1996):

1. Uncertainty of the process (methodology)
2. Uncertainty of the assessor(s) (human error)
3. Uncertainty about the organism (biological and environmental unknowns)

The goal is to reduce these levels of uncertainty as much as possible. Basing the risk assessment methodology on robust scientific knowledge and statistical analyses of past introductions will do much to minimise the first source of uncertainty.

Uncertainty of the assessor(s) is best handled by having the most qualified and conscientious persons available conduct the assessments. The quality of the risk analysis will, to some extent, always reflect the quality of the individual assessor(s) (Aquatic Nuisance Species Taskforce 1996). Some of the information used in performing a risk assessment is scientifically defensible, some of it is anecdotal or based on experience, and all of it is subject to the filter of perception. Hence all risk assessments contain a subjective component. Ensuring the assessors have no vested interest in the outcome leading to a conflict of interest, and that they are appropriately qualified, will reduce errors introduced by this second source of uncertainty. The caliber of a risk assessment is related to the quality of data available, so ensuring that a thorough and comprehensive literature review is undertaken for each species assessed, and that the risk assessment is reviewed by scientists familiar with the species being assessed, can reduce the third source of error.

Species for which little biological data are available represent a risk and although this risk may be small for individual species, the risk becomes much higher if lack of ‘demonstrated risk’ is used as grounds to import large numbers of species for which a risk cannot be demonstrated due to lack of supporting biological data (Aquatic Nuisance Species Taskforce 1996).

It is important that regulatory agencies take steps to establish and maintain a clear conceptual distinction between assessment of risks and consideration of risk management alternatives. The scientific findings embodied in risk assessments should be explicitly distinguished from the political, economic, and technical considerations that influence the design and choice of regulatory strategies (Aquatic Nuisance Species Taskforce 1996). Hence risk managers should not attempt to influence the outcome of an assessment and should ensure that those conducting assessment are free from any pressures or motives that might influence the outcome.

Section 1: Review of factors affecting the potential of an exotic fish to establish a free-living population in the wild

1.1 Establishment success rates

According to some ecologists, only about 10% of exotic introductions to the wild succeed in establishing (Williamson 1996, 1999; Williamson and Fitter 1996; Holmes 1998; Ricciardi and Rasmussen 1998; Enserink 1999; Smith et al. 1999). Analyses of past introductions of exotic birds, mammals and fish reveal that this generalisation is doubtful for vertebrates. Arthington et al. (1999) compiled records of 2467 introduction events of 352 freshwater finfish species outside their geographic range around the world, and found 1263 (51%) of these introductions resulted in the species establishing. This is a similar finding to that reported by other authors. Ross (1991) examined 31 papers studying the introduction of exotic fish to 26 aquatic systems and found establishment success varies from 38% to 77%. Welcomme (1988) examined 1354 records of 237 exotic fish species introductions into 140 countries between 1800 and 1985. He found that in 22.0% of introductions the species did not establish. In a further 18.2% of introductions the species did not breed under natural conditions and was only maintained by continuous imports. In 33.5% of introductions the species established and maintained either an isolated small population or a widespread population at very low density. The introduced species became a significant or dominant element in their new habitat in 23.7% of introductions. In the remaining 2.6% of introductions the species established and became a dominant element in the environment but then declined, to low numbers or extinction either naturally or through deliberate eradication attempts. These data may be biased in favour of successful introductions, and if more unsuccessful introductions were recorded, the reported success rates could be lower (Welcomme 1988; Moyle and Light 1996b; MacIsaac et al. 2001). Unsuccessful introductions may only be reported for easy to detect species or species that are frequently released or released in well-surveyed sites. Considering the data of Ross (1991), Welcomme (1988) and Arthington et al. (1999) it is likely that around 50% of exotic fish introductions result in established populations although the figure varies between fish taxa and in different locations. This is a similar percentage to that reported for both exotic birds and mammals (Bomford 2003) and so is perhaps general across vertebrate taxa.

1.2 Predicting establishment success

Assessing invasion risk relies on identifying factors that are linked to the probability of successful establishment if a new fish species were introduced and released in Australia. There is a considerable scientific literature on the ecological theory of species' invasions, proposing a suite of factors that may influence whether or not exotic vertebrates establish in new environments. These factors are evaluated below with an assessment of their practical significance for predicting the risk of new finfish species establishing in Australia.

1.2.1 Key factors that are predictive for establishment success

There are five key factors for which there is strong evidence of a correlation with establishment success:

(i) Number of release events – propagule pressure

The release of large numbers of animals at different times and places (high propagule pressure) enhances the chance of successful establishment (Case 1991; Daehler and Strong 1993; Moyle and Light 1996b; Townsend 1996; Arthington et al. 1999; Grevstad 1999; Duncan et al. 2001; Kolar and Lodge 2001; MacIsaac et al. 2001; Mack and Lonsdale 2001; Ricciardi 2001; Forsyth et al. 2004). Small populations (or small propagules of released animals) are more susceptible than large populations to extinction from factors such as increased risk of predation, not finding a mate, reduced breeding success or poorer hunting success or increased inter-specific competition (Soule and Simberloff 1986; Williamson 1989; Arthington et al. 1999; Dennis 2002). Demographic stochasticity, such as random fluctuations in the proportions of males and females, will play a major role in determining the survival of small populations, particularly for short-lived or monogamous species (May 1991; Lande 1993; Legendre et al. 1999).

Environmental stochasticity, including chance events such as droughts and floods, are also likely to drive small populations to extinction (MacArthur and Wilson 1967; Simberloff 1989; Williamson 1989; Stacey and Taper 1992; Caughley 1994; Caughley and Sinclair 1994). Small populations may also lose genetic variability which may reduce the probability of long-term survival (Soulé 1987; May 1991). Ehrlich (1989) suggests that the release of more individuals may increase success rates because larger invading groups will have a greater pool of genetic variability. This might reduce founder effects and enhance the chances of rapid adaptive radiation in the new environment. The minimum viable population size for successful invasion is not known for most species.

Repeated releases over an extended period will increase the chance of successful invasion simply because the release 'experiment' is repeated many times, under different biotic and abiotic conditions, including different climates and seasons, condition of released animals and numbers of natural enemies present.

Evidence: An analysis of worldwide fish introductions (Figure 1, data in Appendix D, Table D1) indicates a strong correlation ($R^2 = 0.79$) between the number of times a freshwater fish species is introduced and the number of exotic populations it establishes. All species that had more than ten recorded introduction events had at least one successfully established exotic population recorded. Thus it would appear that many exotic fish species can establish exotic populations if sufficient releases are made. Moyle and Light (1996a) reached a similar conclusion, based on their observations of aquatic systems in California, that most fish species are capable of invading new systems.

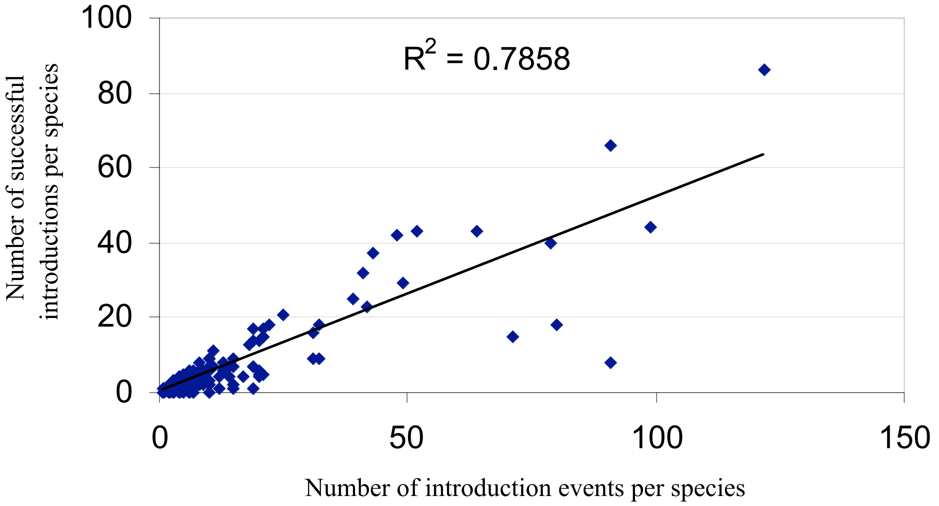

Figure 1. Correlation between the number of introduction events and the number of successful introductions for 352 freshwater finfish species introduced around the world (Data collated from Arthington et al. 1999).

No assessment was made of the other two components of propagule pressure, number of fish released and of locations where releases were made, because little information is generally available on these factors.

Risk assessment significance: The number of release events is a significant predictor of establishment success, and the total number of individuals released and the number of sites at which releases occur may also affect establishment success. These three variables, which collectively determine the level of propagule pressure, should be considered as key factors when managing the risk of exotic species establishing in Australia. The number of fish that escape or are released is likely to increase if more species are kept, in higher numbers, and in more locations. Hence, propagule pressure can be reduced by restricting which species are kept in Australia, the number of collections holding a species, the number of individuals held in each collection, and the security conditions for keeping species and by educating people about the risks of releasing exotic fish into waterways. Any changes to policy or management for exotic species that allow more species to be imported, or reduce restrictions on where exotic species can be held or the numbers held, are likely to increase the risk that more exotic fish species will establish wild populations in Australia.

(ii) Climate match

A frequently stated hypothesis in the biological invasion literature is that species should have a greater chance of establishing if they are introduced to an area with a climate that closely matches that of their original range (Moyle 1986; Brown 1989; Williamson 1996; Davis et al. 1998; Arthington et al. 1999). Climate match is a measure of the similarity between the sites of origin and release based on rainfall and temperature data. The environmental condition of water bodies in a region is broadly determined by climate. Potential species' ranges are predicted using a 'climate envelope' approach, in which the current distribution of a species is mapped and its climatic attributes measured, and then potential new locations with matching climate attributes are determined and mapped. Climate matching can be used to generate maps of probability of successful establishment of a species from any part of the world to a nominated target region (Nix and Wapshere 1986; Pheloung 1996; Ricciardi and Rasmussen 1998; Sutherst et al. 1998; Baker et al. 2000; Duncan et al. 2001; Kriticos and Randall 2001; Forsyth et al. 2004). The suitability of Australian environments for the establishment of a species can be quantified on a broad scale by measuring the climate match between Australia and the overseas geographic range of a species. Arthington et al. (1999) consider the most limiting environmental factor in Australia's freshwater affecting exotic finfish establishment is temperature. Water temperature is a major determinant of whether exotic fish establish breeding populations (Nico and Fuller 1999). Brown (1989), however, cautions that many animals can tolerate a much wider range of physical conditions than that in their current range which would mean that climate matching would tend to give conservative estimates of potential range. On the other hand, climate matching does not take account of the biotic factors in the potential area of introduction, including natural enemies (competitors, predators, diseases and predators) or food requirements that may reduce the suitability of an area for establishment even if the climate is suitable (see Section 1.2.2ii). Species that have a large overseas range over several climatic zones are predicted to be strong future invaders (even if they have not yet spread to new continents) (Daehler and Strong 1993).

Evidence: A comparison of the 31 species of exotic fish established in Australia with the 19 species introduced but not established (Appendix A, Table A1; Appendix E, Table E1, Figure E1) indicates that successfully introduced species in Australia have a greater area of climatically matched habitat than species that failed to establish. This relationship also holds for exotic mammals and birds introduced to Australia (Duncan et al. 2001; Forsyth et al. 2004) and so may be generally applicable to exotic vertebrates.

Risk assessment significance: The level of climate match should be considered as a key factor when assessing the risk that new exotic species could establish in Australia. The climate match between a species' overseas geographic range and mainland Australia can be determined using CLIMATE software (Pheloung 1996). Species with a high climate match to Australia are most likely to establish here. However, climatic match alone is not sufficient to ensure an exotic fish will be able to survive and reproduce. Climatic matching only sets the broad parameters for determining if an area is suitable for an exotic fish to establish. Many factors, such as unsuitable water chemistry or flow dynamics, the absence of suitable spawning habitats or food, or the presence of competitors, predators or diseases, could prevent an exotic fish from establishing in a climatically matched area, so that climate matching would overestimate the area of suitable climate in Australia. On the other hand, these same biotic and non-climate related abiotic factors could prevent a species from spreading to surrounding areas with suitable climate from its native or current introduced range (Taylor et al. 1984), and in such a case, climate matching could underestimate the area of suitable climate in Australia.

(iii) History of establishing exotic populations elsewhere

A proven history of establishing exotic populations may indicate that a species has attributes that increase the risk of it successfully establishing in other areas (Bomford 1991, 2003; Daehler and Strong 1993; Williamson 1996, 1999; Ricciardi and Rasmussen 1998; Arthington et al. 1999; Kolar and Lodge 2002; Hayes and Sliwa 2003).

Evidence: Kolar and Lodge (2002) found that fish species that successfully established in the Great Lakes of North America were more likely to have been introduced successfully elsewhere than fish that failed to establish.

A comparison of the 31 species of exotic fish established in Australia with the 19 species introduced but not established (Appendix A, Table A1) indicates that successfully introduced species in Australia are more likely to have established exotic populations elsewhere than the fish that failed to establish. This relationship also holds for exotic mammals and birds introduced to Australia (Duncan et al. 2001; Forsyth et al. 2004) and so may be generally applicable to exotic vertebrates.

Risk assessment significance: Because a history of establishing exotic populations elsewhere is a significant predictor of establishment success for exotic fish introduced to Australia and to the Great Lakes of North America, this variable should be considered as a key factor when assessing the risk that exotic fish could establish here. However, many species that are potential exotics have not been transported to and released in new environments, so they have not had the opportunity to demonstrate their establishment potential. Hence, caution should be applied when using a history of establishment elsewhere to predict a species' establishment potential in Australia if the species being assessed has little or no history of previous introductions.

(iv) Overseas geographic range size

Species that are widespread and abundant in their original range are more likely to establish exotic populations than species with more restricted ranges (Brown 1989; Daehler and Strong 1993; Ricciardi and Rasmussen 1998; Duncan et al. 2001; Bomford 2003; Forsyth et al. 2004).

Williamson (1996) suggests a wide geographic range could indicate flexible or generalist species, or good dispersers, and hence species that are more likely to invade successfully. Exotic species with an ability to tolerate wide habitat and climatic variability may be more successful at establishing (Swincer 1986; Ehrlich 1989).

Evidence: A comparison of the 31 successfully established species of exotic fish in Australia with the 19 species that were introduced but failed to establish indicates that the successful species have a higher number of 1^{o} latitude by 1^{o} longitude grid squares in which their occurrence is recorded in Fishbase (2004) (excluding Australian records) than the failed species (Appendix F, Table F1). This relationship between overseas range size and establishment success also holds for exotic mammals and birds introduced to Australia (Duncan et al. 2001; Forsyth et al. 2004) and so may be generally applicable to exotic vertebrates.

Risk assessment significance: Overseas geographic range size should be considered a key factor when assessing the risk that new exotic species could establish in Australia, because having a widespread overseas geographic range is a significant predictor of establishment success for exotic fish in Australia.

(v) Taxonomic group

Some ecologists consider that fish species that are closely related to fish with a history of being invasive present a higher risk of establishing in Australia (Moyle 1986; Arthington et al. 1999). Daehler and Strong (1993) suggest this risk may be enhanced if the closely related species has similar habits to the known invader.

Evidence: Moyle (1986) looked for patterns of fish introductions to North America and found that the majority of species that have become established outside their natural range come from the families Salmonidae, Cyprinidae, Ictaluridae, Poeciliidae, Cichlidae, Centrarchidae and Percidae. Moyle (1986) also noted that most other finfish families have at least one species that has been a successful invader.

An analysis of the number of introduction events and the number of successful introductions for 352 freshwater finfish species from 53 families and 132 genera introduced around the world indicates that both family and genus are highly significantly correlated ($p< 0.001$) with introduction success rate (data collated from Arthington et al. 1999). Table 2 presents the establishment success rates for families worldwide in decending order of success. Table 2 indicates that the seven most successful families are Gobiidae, Cobitidae, Poeciliidae, Clupeidae, Loricariidae, Atherinidae and Osteoglossidae. Other families, such as Osmeridae, Sciaenidae and Cyprinodontidae, may have the potential to be similarly successful, but there are as yet insufficient records of introductions of representative species from these families to adequately assess their invasiveness.

Risk assessment significance: For fish species with a history of introductions to new areas, or with relatives in the same family with such a history (listed in Table 2), previous establishment success rates should be considered a key predictor of future establishment success. A precautionary approach to their introduction may be advisable for fish that have little or no introduction history, and without relatives with an introduction history.

Table 2. Establishment success rates for introduction events of families of freshwater finfish introduced outside their geographic range worldwide in decending order of success. Includes only families for which there are records of five or more introduction events* (data collated from Arthington et al. 1999).

Family	**Number of introduction events**	**Number of successful introductions**	**Success rate %**
Gobiidae	16	14	88
Cobitidae	8	7	88
Poeciliidae	172	144	84
Clupeidae	10	8	80
Loricariidae	5	4	80
Atherinidae	8	6	75
Osteoglossidae	8	6	75
Ictaluridae	105	70	67
Percidae	33	22	67
Channidae	15	10	67
Umbridae	9	6	67
Gasterosteidae	6	4	67
Belontiidae	47	31	66
Centrarchidae	171	112	65
Siluridae	15	9	60
Anabantidae	7	4	57
Esocidae	16	9	56
Cichlidae	466	252	54
Fundulidae	6	3	50
Catostomidae	25	12	48
Cyprinidae	707	316	45
Anguillidae	21	9	43
Centropomidae	10	4	40
Apocheilidae	5	2	40
Salmonidae	381	150	39
Clariidae	47	18	37
Osphronemidae	19	7	37
Moronidae	14	5	36
Helostomatidae	7	2	28
Characidae	33	4	12
Acipenseridae	28	1	4
Pangasiidae	5	0	0
Adrianichthyidae	6	0	0

* Data for families for which fewer than five introductions have been recorded are presented in Appendix D, Table D1.

1.2.2 Additional factors that have been suggested to have a role in establishment success

There are many additional factors that are hypothesized to enhance the probability of establishment but for which scientific supporting evidence is currently lacking or equivocal. Eighteen such factors are listed below with a brief assessment of their predictive value for risk assessment.

(i) Rate of population increase and related variables

Many ecologists consider that high fecundity (average number of females produced by females surviving to reproductive age) and associated attributes (rapid growth rates and early sexual maturity, large clutch size, frequent spawnings and extended spawning period, high breeding frequency, short gestation and opportunistic or aseasonal breeding) contributes to successful vertebrate invasions (Taylor et al. 1984; Moyle 1986; Kailola 1989; Fryer 1991; Crowl et al. 1992; Lodge 1993a; Ricciardi and Rasmussen 1998; Arthington et al. 1999; Elvira 2001; MacIsaac et al. 2001). Such traits are often referred to as *r*-selected. The intrinsic rate of increase (*r*) of a species might be expected to determine the speed with which a small founding population can rise above the critical threshold number needed for demographic viability. Some ecologists suggest vertebrates with short generation times should be more successful invaders than those with long generation times (Ehrlich 1989; Lockwood 1999). In contrast, Crawley (1986) suggests high adult longevity ensures that offspring are produced over a protracted period, thus enhancing the probability of establishment by increasing the chances that offspring will encounter suitable conditions for establishment. Lodge (1993a) suggests *r* may not be an important determinant of invasion success for fish.

Evidence: Kolar and Lodge (2002) found that fish that successfully established in the Great Lakes of North America had faster relative body growth rates (an *r*-selected trait) than fish that were introduced but failed to establish. Bruton (1986), however, found a more or less equal representation of *r*-selected and *K*-selected (slow growing, low rate of increase, long generation times) species in invasive fish species of South Africa.

Risk assessment significance: The evidence supporting a link between factors associated with a high *r* value and high establishment success is limited and equivocal. Data for measuring *r* are also unavailable for many fish species. Therefore it is unlikely that factors associated with *r* will be useful for predicting the probability of establishment success at present.

(ii) Suitable site — resources and enemies and 'biotic resistance'

The availability of habitat near the release site that meets a species' physiological and ecological needs is necessary for establishment (Welcomme 1988; Case 1991; Ross 1991). Introduced fish need refuges near the release site where they can obtain food, water, shelter and protection from natural enemies. Both habitat disturbance and an absence or low occurrence of natural enemies such as predators, competitors, parasites or diseases are often suggested to favour establishment (Mandrak 1989; Crowl et al. 1992; Moyle and Light 1996a). Fish that are ecologically or behaviourally distinct from fish in receptor habitat may have an advantage in establishing either because the resident fish do not compete with them or are the losers in such interactions.

Some ecologists consider that biotic conditions in the recipient habitat play a major role in determining introduction success, in particular that the presence of natural enemies (predators, competitors, parasites or diseases) may resist invaders and that therefore species-rich diverse communities are more resistant to invasion than species-poor communities (Pimm 1989; Case 1991; Lever 1996; Moyle and Light 1996a; Elvira 2001). The importance of competition and disease as a cause of failure may be underestimated because these factors are difficult to measure and so their effects are rarely assessed. Habitats where there are no resident species that have an ecological strategy similar to the introduced exotic species may be more likely to be invaded because the new species can fill a 'vacant niche' without competition from species with similar ecological strategies. Conversely, habitats where similar species that may become competitors or predators are present may have a 'biotic resistance' to being invaded (Welcomme 1988; Case 1991; Ross 1991). Hence some ecologists have suggested habitats with high levels of species diversity, and hence presumably large numbers of potential predators and competitors, will have higher levels of 'biotic resistance' and hence will be more resistant to invasion. For example, based on his examination of 1354 introductions of 237 exotic fish species into 140 countries, Welcomme (1988) suggests that habitats with low levels of species diversity are more likely to be successfully invaded than more species-rich communities. He gives examples of two freshwater species-poor habitats where the establishment rate of introduced fish has been high. In freshwater systems on tropical islands the introduction success rate of all fish was 73.3 % and in high altitude lakes and rivers in the tropics the introduction success rate of salmonids was 73.1%. Moyle (1986) found similar high introduction success rates in species-poor communities in the western drainage systems of the United States. Similarly, Ross (1991) assessed 31 papers studying the introduction of exotic fish to 26 aquatic systems and found the establishment of exotic fish was higher in areas that had fewer native fish.

Ricciardi and MacIsaac (2000) point out that although examples exist where natural enemies have repelled invaders, many complex aquatic systems have been invaded multiple times, such as Lake Victoria and the Caspian Sea. Similarly Fryer (1991) cited examples of invasion by fish of Lake Malawi, which has a rich fish fauna and some of the most complex of all freshwater fish communities, showing how easily some highly diverse tropical ecosystems can be invaded. Moyle and Light (1996a) note that exotic fish have become established in many lakes and streams that originally had no fish, as well as in complex assemblages with high species diversity and this observation conflicts with one of the most well established generalisations of the aquatic invasion literature, that systems with low diversity and complexity are the most susceptible to invasion (Lodge 1993b). So Moyle and Light (1996b) conclude that the frequently cited generalisation that community diversity reduces invasion success (Lodge 1993a,b) is not supported by examples from aquatic systems. Based on their studies of invading fish in Californian streams and estuaries, Moyle and Light (1996a, b) contend that all aquatic systems are invasible regardless of the biota already present, if abiotic conditions are appropriate. Ricciardi (2001) draws the same conclusion from studies of the invasion history of the American Great Lakes. Thus it appears likely that the abiotic components of the environment have the principal role in determining establishment success.

The theory of biotic resistance predicts that communities become more resistant to invasion as they accumulate more species, because species accumulate that have been successful competitors or predators, as demonstrated by the success of their original invasions (Case 1991; Moyle and Light 1996a). In contrast to this theory, some ecologists have suggested that invasions may be assisted by previous invasions, and that pre-established exotic species appear to facilitate the establishment of later arriving exotic species (Ricciardi 2001). This is a pattern opposite to that predicted by the biotic resistance hypothesis (Simberloff and von Holle 1999; Ricciardi 2001). Simberloff and Von Holle (1999) proposed that as the cumulative number of attempted and successful introductions increases, each perturbing the system and possibly facilitating one another, the recipient community becomes more easily invaded over time. Chronic exposure to introduced species thus subjects a community to 'invasional meltdown' (an accelerated rate of invasion) particularly when there are facilitative interactions between coevolved invaders. Hence, the widely cited view in relation to terrestrial communities, that species-rich communities are resistant to invasion or become increasingly resistant with each species addition, is apparently invalid for aquatic systems subject to frequent human-mediated introductions (Ricciardi and MacIsaac 2000; Ricciardi 2001). For example, Moyle and Light (1996b) suggest the invasion of the American Great Lakes by salmonids *Oncorhynchus* spp. was greatly facilitated by disruption of the lake ecosystem by two previous invading fish, the sea lamprey *Petromyzon marinus* and the alewife *Alosa pseudoharengeus*.

Because of these currently conflicting views among ecologists regarding the role of biotic resistance and the possible facilitation of invasion by previous invaders, it is not possible to draw general conclusions about the susceptibility of ecological systems to invasion based on their biotic components (Moyle and Light 1996b; MacIsaac et al. 2001).

Evidence: The role of natural enemies in establishment success is difficult to measure and limited quantitative evidence could be found to support this theory. Evidence is equivocal whether the level of species diversity or the presence of previous invaders in receptor habitat is correlated with introduction success.

Risk assessment significance: No consistent patterns between community structure and susceptibility to invasion have been demonstrated for fish and therefore variables describing the biotic components of receptor habitats are unlikely to have predictive value unless long-term intensive studies on community interactions in relation to the physiological and life history requirements of the species proposed for introduction are first conducted. The potential relationships between an organism and possible parasites, predators, diseases and competitors are usually impossible to predict, except in a generalised, qualitative sense. These factors are difficult or expensive to measure quantitatively, so there is little evidence to support or reject their role in establishment success. Hence, these factors are unlikely to be of value for risk assessment and management. It would also be extremely difficult to rank habitat suitability objectively, so this factor probably has limited value for quantitative risk assessment except for separating disturbed habitat from undisturbed habitat and for climate matching. The significance of the availability of suitable microhabitats and microclimates for fish is largely unknown. Hence, it is difficult to quantify microclimate variables in a way that would be useful for managing the risk of species establishment.

(iii) Environmental tolerances for abiotic conditions

Fish that are able to survive and reproduce under a wide range of conditions may be more likely to establish than those less tolerant (Taylor et al. 1984; Arthington and Mitchell 1986; Kailola 1989; Pimm 1989; Crowl et al. 1992; Ricciardi and Rasmussen 1998; Arthington et al. 1999; Nico and Fuller 1999; Elvira 2001). In addition to climate-related factors such as temperature (Section 1.2.1ii) environmental variables include hydrologic regime, oxygen levels, salinity, hardness, acidity, turbidity and pollution (Moyle and Light 1996a; Arthington et al. 1999). Cichlids, cyprinids and some poeciliids can survive for some time in water temperatures as low as 5°C and as high as 43°C, freshwater and hypersaline waters, polluted and/or de-oxygenated waters (Taylor et al. 1984; Arthington et al. 1999). Elvira (2001) gives the examples of mosquito fish *Gambusia affinis* and *G. holbrooki* that can survive temperature ranges of 6–35°C, extremely low oxygen concentrations and salinities as high as twice that of seawater.

Harsh environmental conditions in relation to the physiological capabilities of a fish, including salinity, water hardness, turbidity, acidity, whether high or low values or highly variable, unpredictable values, can override a good climate match, and make a particular water body unsuitable for a potential invader.

Moyle and Light (1996a,b) suggest a close match between an invader's physiological and life history requirements and the abiotic components of the invaded system will determine invasion outcomes, regardless of biotic resistance. Climate matching (Section 1.2.1ii) is one component of the abiotic environment. Another abiotic component of an invaded aquatic system, which Moyle and Light (1996a,b) consider plays a large role in determining invasion success, is the hydrologic regime. The hydrologic regime includes such factors as flow speeds, turbulence, depth, volumes and seasonal patterns or unpredictable random changes to these factors. These may be broadly correlated with climate, but also are affected by factors such as altitude, geology, salt-water encroachment, catchment land use and human constructions (such as dam building, channeling, stream diversion and irrigation). Stream and lake bottom and bank structures and sediments may also be important. For example, trout have been unable to establish in many slow-moving Australian rivers within their natural thermal tolerance range because of the paucity of suitable spawning substrates (Weatherley and Lake 1967) and the torrential waters and coarse substrates of river headwaters may act as barriers to upstream movement of European carp (Arthington et al. 1999).

Species able to tolerate the high water temperatures and severe hypoxic conditions of many floodplain water bodies may be better invaders (Fryer 1991; Arthington et al. 1999; Nico and Fuller 1999; Kailola 2000). The ability to breath atmospheric air is a huge advantage to dispersal, and its advantage is well illustrated by taxa such as walking catfish *Clarias batrachus*, snakeheads *Channa* spp and climbing perch *Anabas testudineus* that have established in New Guinea (Kailola 2000). However, Fryer (1991) points out in contrast that the ancient lung fishes (Dipnoi) are also air breathers but this taxon is not a good invader. Being able to tolerate the high water temperatures and severe hypoxic conditions of many floodplain water bodies may enhance invasion success (McNeil and Closs 1998). For example, European carp and goldfish have high tolerance to hypoxia, the mosquito fish *Gambusia holbrooki* has a particularly efficient use of aquatic surface respiration and the weatherloach tolerates hypoxia by gulping air at low oxygen levels (McNeil and Closs 1998). These four exotic species in Australia are the most widespread of Australia's freshwater exotic fish (Kailola 2000).

Evidence: Kolar and Lodge (2002) found that fish species that successfully established in the Great Lakes of North America tolerated wider ranges of temperature and salinity than fish species that failed to establish.

A comparison of the tolerances for salinity, acidity and water hardness for exotic fish that established or failed to establish in Australia following their introduction indicated wide variability within both groups and no indication that the species that established had broader tolerances (Appendix C, Table C1).

Only anecdotal evidence was found to support a link between tolerance to hypoxic conditions and establishment success.

Moyle and Light (1996b) found that in Californian streams, invading fish are most likely to be successful if they are adapted to the local, highly seasonal stream flow conditions. Lodge (1993a) also found evidence supporting the importance of hydrologic regimes in the invasion success of fish in mid-western lakes in the USA.

Risk assessment significance: While climate matching can provide a broad envelope of suitable environmental conditions, fish also require suitable hydrologic regimes that meet their physiological and life history requirements. Only detailed studies of conditions where releases are going to occur will determine if such requirements are met. If such studies are not available, it is probably reasonable to assume that these requirements will be met, especially for fish species with broad environmental tolerances.

(iv) Genotypic and phenotypic variability and behavioural flexibility

Animals with high genotypic and phenotypic variability may be more successful at establishing (Townsend 1996; Vermeij 1996; Ricciardi and Rasmussen 1998; Arthington et al. 1999; Kailola 2000; Elvira 2001; MacIsaac et al. 2001). Behavioural flexibility may also be an advantage. One of the chief reasons for the global success of brown trout is its polytypic nature – it naturally occurs as a series of reproductively isolated stocks each with slightly different characteristics (Townsend 1996). This is probably also the case for European carp and goldfish strains (Kailola 2000).

High genotypic and phenotypic variability in diet, behaviour and nesting habits in different environments may increase establishment success because high variability increases the potential for rapid adaptive radiation. Fish are generally more plastic in their potential for hybridising than are mammals and fewer crosses between fish species result in sterile progeny (Welcomme 1988). Hybrids may be produced spontaneously and survive in the wild. Such hybrids may be better adapted to survival and breeding than parent stock and be more invasive.

Evidence: According to Arthington et al. (1999), various studies have shown that some fish groups (notably cichlids and cyprinids) acclimatise over generations to 'less suitable' environments. However, no quantitative evidence could be found to support the theory that high genotypic and phenotypic variability enhances establishment success. Some successful animal invaders have very low heterozygosity (Moller et al. 1993).

Risk assessment significance: Fryer (1991) and Williamson (1996) consider that genetics will have little to offer for the predicting likelihood of establishment for exotic species. Fryer (1991) considered that genetic changes that take place in newly established populations reflect reaction and adaptation to the new environment rather than any genetic features favouring invasion.

(v) Dispersal ability

Fish with good dispersal abilities may be better invaders perhaps because they are better able to seek out habitats suitable for survival and reproduction (Moyle 1986; Kailola 1989; di Castri 1990; Ricciardi and Rasmussen 1998; Arthington et al. 1999; MacIsaac et al. 2001). Moyle (1986) considers the ability to disperse rapidly from the point of introduction to be one of the most important characteristics of a successful introduced fish species. He found that impressive dispersal records existed for many of the introduced fish species of North America.

Evidence: No quantitative evidence could be found to support this theory. Fryer (1991) was unable to find any empirical studies which demonstrated a consistent relationship between dispersal ability and invasion success. He pointed out that some fish species, like *Clarias gariepinus* and *Oreochromis niloticus* which have seemingly poor dispersal abilities, have been hugely successful as invaders. Kolar and Lodge (2002) assessed the dispersal rates of 16 exotic fish species successfully introduced to the American Great Lakes and ranked seven species as slow spreaders and nine species as fast spreaders

Risk assessment significance: Dispersal ability is generally a difficult trait to quantify and if evidence from fish invaders of the American Great Lakes is applicable elsewhere, it is unlikely to be a useful factor for predicting establishment success.

(vi) Broad diet

Some ecologists suggest animals with broad and/or flexible diets (dietary generalists) may be more successful at establishing exotic populations than those with restricted diets (dietary specialists) because their flexibility would enable them to exploit a greater range of food types than dietary specialists, so reducing the chances of food being limiting (Taylor et al. 1984; Arthington and Mitchell 1986; Kailola 1989, 2000; Crowl et al. 1992; Ricciardi and Rasmussen 1998; Arthington et al. 1999; Nico and Fuller 1999; MacIsaac et al. 2001). For example, the successful invader Mozambique tilapia is normally a herbivore–detritivore but is known to switch to carnivory in some circumstances (Arthington and Bluhdorn 1994).

Evidence: No evidence was found in the literature supporting this theory for fish introductions. However, many of the exotic fish species that have been introduced both in Australia and overseas are dietary generalists, so analyses comparing successful and failed introductions lack statistical power to discriminate on diet. Hence the hypothesis remains largely untested and the role of a generalist diet in enhancing establishment success remains an expert opinion supported by many ecologists rather than an established relationship.

Risk assessment significance: Because many ecologists consider having a generalist diet increases the probability of establishment success, and because nearly all exotic vertebrates established in Australia do have generalist diets, this variable could be considered as a possible contributory factor when assessing the risk that new exotic species could establish here.

(vii) Ability to live in human-disturbed habitats – human commensalism

Many ecologists consider that an ability to live in human-modified or other disturbed habitats (human commensalism) is a major factor contributing to establishment success (Moyle 1986; Ross 1991; Lever 1996; Moyle and Light 1996a,b; Williamson 1996; Ricciardi and Rasmussen 1998; Arthington et al. 1999; MacIsaac et al. 2001).

The success of human commensals may be partly due to many exotic animals coming from, and taking up residence in, human-modified habitats, where the types of food and shelter they are adapted to are present, so there is little need for their ecological niche to change for successful establishment. Exotic species, which are pre-adapted to the types of habitat, food, shelter, predators or diseases present in Australia, may be more successful at establishing.

Moyle and Light (1996a) predict that in aquatic systems with high levels of human disturbance, a much wider range of species can invade than in systems with low levels of human disturbance and these invaders are much more likely to succeed. They suggest this is because human-disturbed systems, such as reservoirs, tend to resemble one another over broad geographic areas so introduced species may be pre-adapted to these types of habitats.

Disturbed habitats may be more susceptible to invasion than undisturbed ones for three main reasons. Firstly, new, unoccupied niches may be created in disturbed habitats. Secondly, activities associated with water management may protect newly introduced small populations from environmental hazards, such as drought, flooding, parasites, predators and competitors, and hence allow them to grow to a size where they are not threatened with extinction by chance environmental events. Thirdly, disturbed habitats often are able to support a high level of species diversity because environmental variation prevents any one species from dominating other species (Connell 1978; Moyle and Light 1996b). Environmental patchiness can facilitate the coexistence of introduced species with potential competitors and predators (Anderson and May 1981; Crowl et al. 1992). Moyle and Light (1996b) suggest that the most invasible systems are those with intermediate levels of human disturbance. Frequent and unpredictable fluctuations in environmental conditions make it difficult for any one species or group of species to dominate the system and this permits species to co-exist that might eliminate one another in more predictable systems or that would be eliminated by environmental conditions in more highly disturbed/altered environments (Moyle and Light 1996b). Changes in competitive ability can be related to environmental changes so that in constantly shifting natural environments no clear winner can emerge (although exceptions are tropical lakes, desert springs or reservoirs which are relatively constant environments). Similarly, Moyle and Light (1996b) suggest the existence of large populations of predators can presumably prevent invasions but only if the environment stays constant enough to maintain the large populations – unusual floods, droughts or human disturbance can upset this biotic resistance. In general Moyle and Light (1996b) conclude that biotic resistance in form of predators, competitors and diseases are less important than environmental resistance (habitat/climate matching) except perhaps in the early stages of an invasion when numbers of the invader are low (see Section 1.2.2ii).

Many successful invaders use dispersal mechanisms that involve human activities. Hence, human commensals may have greater opportunity for establishing rather than having an intrinsic ability to be better at establishing.

Generalist invaders capable of withstanding disturbed conditions associated with urban and industrial pollution and low oxygen levels may be more successful than species which require better environmental conditions because many fish releases occur in disturbed and polluted waters in or near human settlements (Moyle and Light 1996b). Habitat disturbance and the modification of waterways and flow regimes have provided habitats for which introduced species are often better adapted than native fish (Arthington et al. 1999).

Evidence: Ross (1991) examined 31 papers studying the introduction of exotic fish to 26 aquatic systems and found establishment success was generally higher in systems disturbed by human activities. However, despite the high numbers of exotic species found in many highly disturbed aquatic systems (Moyle and Light 1996a,b), there are also many records of exotic fish establishing in relatively pristine habitats, for example Arthington and Bluhdorn (1995) record Mozambique tilapia established in relatively undisturbed areas of Queensland.

Moyle (1986) and Arthington et al. (1990) reviewed the role of habitat disturbance in the establishment of exotic fish species in North America and Australia and found that, although fish have been introduced to many environments, success was highest where waters had been dammed, diverted or otherwise modified to create reservoirs and or more constant flow regimes.

Risk assessment significance: Because many ecologists consider an ability to live in disturbed habitats increases the probability of establishment, and because most successfully established exotic vertebrates are human commensals, this variable could be considered as a possible contributory factor when assessing the risk that new exotic species could establish here. However, it is necessary to recognize that while environmental disturbance may enhance probability of success, it is also possible for exotic fish that live in disturbed environments to establish in undisturbed areas. Moyle and Light (1996b) concede that their finding that the most invasible systems are those with intermediate levels of human disturbance is probably too broad a generalisation to be useful for predicting invasion success.

(viii) Give birth to live young, are mouth brooders or exhibit parental care of eggs or young

Giving birth to live young (for example guppies), being a mouth brooder (for example *Gambusia* spp), or exhibiting parental care of eggs or young, may enhance survival and hence increase the probability of establishment (Arthington et al. 1999; Kailola 2000; Elvira 2001).

Guarding of free-swimming young, as seen in cichlids and the walking catfish, may enhance survival over that of native species with less advanced or no parental care and hence promote establishment success (Taylor et al. 1984; Arthington et al. 1999; Nico and Fuller 1999).

Evidence: Only anecdotal evidence was found to support this theory. For example, Taylor et al. (1984) suggests that spotted tilapia *Tilapia mariae*, black acaras *Cichlasoma bimaculatum* and firemouth cichlids *Cichlasoma meeki* are less prone to nest desertion, and hence egg loss to predators, than native fish species in Florida.

Risk assessment significance: A link between establishment success and live births and/or parental care is too uncertain for these factors to be of use for quantitative risk assessment.

(ix) Fertilised female able to colonise alone

Some ecologists suggest that vertebrates in which the fertilised female is able to colonise alone should be more successful than those in which the female alone is unable to colonise (Ehrlich 1989). If a solitary pregnant female can found a population, this may increase the number of opportunities for establishment that occur compared to species that require a larger founding group.

Evidence: No quantitative evidence could be found to support this theory.

Risk assessment significance: Given the lack of evidence supporting this theory, and lack of knowledge about which species would meet this criterion, this factor is unlikely to be of use for assessing the risk of new species establishing.

(x) Piscivore and detritivore/omnivore dietary groups introduced to low-disturbance habitats

From their observations of Californian fish invasions, Moyle and Light (1996a,b) concluded that piscivores and detritivore/omnivores are more likely to succeed in establishing in systems with low levels of human disturbance, than fish from other dietary groups. They suggested this relationship also appeared to be true for fish invasions of other freshwater ecosystems. Moyle and Light (1996b) suggest the success of these two trophic groups is related to the high availability of food during the establishment phase of invasion. They suggest piscivores and detritivore/omnivores use foods 'that rarely seem to be limiting in aquatic systems'.

Evidence: Other than Moyle and Light's (1996b) observations, no evidence was found to support this theory.

Risk assessment significance: Given the lack of quantitative evidence supporting this theory, and lack of knowledge and difficulty of classifying dietary groups into clear categories, it would be difficult to apply this theory to risk assessment. Further, many future releases of exotic fish species are likely to occur in systems with high levels of human disturbance, where this factor does not apply so it is probably of little use for risk assessment.

(xi) Zooplanktivores introduced to lakes

From their observations of Californian fish invasions, Moyle and Light (1996b) concluded that zooplanktivores have a high success rate when introduced to lakes. They suggest this is because the high availability of zooplankton in lakes ensures that food is not limiting during the invasion stage.

Evidence: Other than Moyle and Light's (1996b) observations, no evidence was found to support this theory.

Risk assessment significance: This factor is probably of little use for risk assessment.

(xii) Individual's age and health

A breeding group of fit, healthy young animals would have a better chance than one of less healthy or older animals approaching the end of their reproductive lifespan. The health (including disease status, parasite loading and any stress or debility associated with being kept in captivity) and age (including reproductive lifestage and sufficient lifespan to outlive unfavourable conditions) of the individual animals released may affect establishment chances.

Kailola (2000) speculates that if an introduced species is free of its natural diseases and parasites when it is introduced, this may give it a competitive advantage and so enhance its invasive ability

Evidence: Kailola (2000) presents examples of introduced fish populations that have fewer parasites or diseases than populations of the same species in their endemic range. However, no evidence was found to support the theory that this gives such fish enhanced invasion success.

Risk assessment significance: Given future releases of exotic species are likely to be unintentional or illegal, managers are likely to have little opportunity to affect the age or health of released animals, so these variables are unlikely to be of use for managing the risk of new species establishing.

(xiii) Aggressive behaviour and territoriality

Fish that are very aggressive may eliminate native fish through a combination of predation and competition and so be able to usurp the resources previously used by these native species (Moyle 1986). Territorial behavior may be linked to aggressive behaviour (Arthington et al. 1999).

Evidence: No quantitative evidence was found to support this theory.

Risk assessment significance: This factor has unknown predictive value so it is not of value for risk assessment.

(xiv) Gregariousness

Some ecologists suggest that gregarious fish may be more successful than solitary ones at establishing exotic populations (Ricciardi and Rasmussen 1998; Arthington et al. 1999; Elvira 2001). If they are released in a group, fish which form schools or breeding colonies may be more successful invaders because this behaviour facilitates breeding when numbers are low and may also provide protection from predators, make foraging more efficient, and make water temperature more hospitable (Arthington et al. 1999).

Evidence: No evidence or analyses were found that tested this theory for fish.

Risk assessment significance: No evidence that evaluations of gregarious behaviour will assist in predicting establishment success.

(xv) Body size

Animals with larger body size may be more successful at establishing exotic populations than smaller, related species (Nico and Fuller 1999; Kailola 2000; Duncan et al. 2001).

Fish with a medium body size or larger may have an advantage because they are less likely to be preyed on and may possess enhanced competitive ability. Longevity and fecundity increase with body size, increasing a species' ability to rapidly increase population size and range. Further bigger fish tend to exhibit less variation in population size. Both the latter two factors will reduce the extinction risks associated with populations of smaller fish (Townsend 1996).

Evidence: According to Nico and Fuller (1999) non-indigenous fish in Florida that are most widespread and common are those of medium body size or larger. However, a comparison of the 31 species of exotic fish established in Australia with the 19 species introduced but not established indicates that there is no difference in the mean maximum body size of the two groups (Appendix C, Table C1).

Risk assessment significance: Body size is unlikely to have any value for predicting the probability of establishment success.

(xvi) Source of animals

Wild caught animals are more successful at establishing exotic populations than captive-reared animals (Griffith et al. 1989; Wiley et al. 1992; Snyder et al. 1994; Wolf et al. 1996). Wild caught animals may have better skills in avoiding predators and seeking out mates, food and other resources needed for survival and breeding.

Evidence: No evidence or analyses were found that tested this theory for fish.

Risk assessment significance: This factor has unknown predictive value so it is not of value for risk assessment.

(xvii) Public and government attitudes and actions
Attempts to feed or shelter released animals might increase the chances of establishment. Conversely, attempts to recapture or destroy released animals may reduce the chances of establishment (Bomford 1991). Attempts to feed or shelter released animals may be more likely to occur for attractive or valuable animals and this might assist establishment by providing favourable ‘microhabitats’. Attempts to recapture or destroy released animals may help prevent establishment and are probably more likely to occur if government policies and practices support them.

Evidence: No evidence was found that care following release increases establishment success for exotic fish. Government actions to eradicate newly established populations have sometimes been successful. Such attempts may also fail.

Risk assessment significance: It is uncertain if dedicated assistance can help to establish populations. Attempts to capture or destroy released animals or their progeny may help to reduce the chance of establishment. Public eduction programs may reduce the chances of exotic fish being released.

1.3 Discussion

There is strong evidence that the five key factors listed in Section 1.2.1 are correlated with establishment success for introduced exotic fish. Although it is not possible to demonstrate independent statistically significant correlations between these five factors and establishment success for fish introduced to Australia (Appendices A and B), possibly due to the lack of power of the tests due to small sample sizes, the associations demonstrated are considered to form a valid basis for developing a model to predict the risk posed by future introductions of exotic fish to Australia. Similarly, Kolar and Lodge (2002) did not demonstrate independent statistically significant correlations between the factors they found associated with establishment success for exotic fish introduced to the Great Lakes of North America, yet they also consider the associations they demonstrated form a valid basis for developing a model to predict the risk posed by future introductions of fish to these lakes. A simple quantitative model to predict the risk of new species of exotic fish establishing in Australia is developed in Section 3 of this report.

Few of the factors listed in Section 1.2.2 have been confirmed to be correlated with establishment success. As might be expected from such a taxonomically diverse group as fish, successfully introduced species differ widely from one another in spawning habits, degree of parental care, adult size, feeding habits, dispersal ability, environmental tolerances and many other factors. According to Moyle (1986) there does not seem to be any one biological feature that successfully introduced fish species have in common. Rigorous designed experiments are required to confirm or reject the potential role of these factors (Moyle 1986; Simberloff 1989; Lodge 1993b; Ricciardi and Rasmussen 1998). Fryer (1991) gives examples of the varying combinations of factors that contribute to successful establishment among different exotic fish and provides many examples. Further assessment of these factors was beyond the scope of this project but examination of the literature and fish databases to see if sufficient data are available to conduct quantitative assessments of their associations with establishment success for exotic fish would certainly be worthwhile. In the meantime, these factors should probably be considered in qualitative assessments of risk, in addition to the quantitative risk assessment approach developed in Section 3 of this report. This would be particularly desirable if decisions are being made on whether to import species of exotic fish that score a moderate or higher risk of establishment in the quantitative risk assessment model.

One factor which brings uncertainty to predicting impacts of introduced fish is that a newly introduced fish may adopt a niche that differs completely from that in its native range (Welcomme 1988). For example, introduced cichlids have adapted to living in temperature ranges outside those that are limiting in their home range and allowed normally tropical species to invade sub-tropical or even warm temperate areas (Welcomme 1988).

Moyle and Light (1996b) consider the abiotic conditions of the environment (climate match, hydrologic conditions, water chemistry etc) in relation to the biological characteristics of the invader are by far the most important factors determining invasion success. They consider biotic resistance (competitors, predators diseases etc) is far less significant, although they acknowledge predation may be important in the initial stages of an introduction if the numbers of the invading fish are low. In contrast, Lodge (1993a) considers that the role of predation, competition, disease and other subtle interactions are perhaps just as important as the abiotic conditions but are underestimated because they are more difficult to measure.

Kolar and Lodge (2002) used discriminant analysis and categorical and regression tree (CART) analysis to compare the 24 exotic fish established in the Great Lakes of North America with the 21 species of introduced but not established exotic fish. They collected data from the literature on 13 life-history characteristics, five habitat needs, six aspects of invasion history, and human use to look for factors correlated with establishment. Fish that established in the Great Lakes grew faster, tolerated wider temperature and salinity ranges and were more likely to be invasive elsewhere than fish that failed to establish. In contrast, a comparison of the 31 species of exotic fish established in Australia with the 19 species introduced but not established (Appendix C, Table C1) indicates that successfully introduced species in Australia vary widely in their tolerances for salinity, water hardness and acidity and do not appear to have greater environmental tolerances than unsuccessful fish. However, the comparison of the successful and unsuccessful exotic fish in Australia indicated that successful fish had more climatically matched habitat, had a wider geographic range overseas, were more likely to have established exotic populations overseas and had a higher establishment success rate overseas than the fish that failed to establish in Australia (Appendix A, Table A1). When conducting these types of statistical analyses it is desirable to control for the degree to which the fish in the samples are genetically related to one another as this can bias the results. Unfortunately neither this study on Australian introductions (Appendices A and B) nor Kolar and Lodge's (2002) study performed such phylogenetically corrected analyses because the systematics of fish are not sufficiently understood.

Scientific theory and knowledge is still unable to be used to make certain predictions about the invasive capability of individual species. This uncertainty has led many experts to question whether it is even feasible to try to reliably predict whether exotic animals could establish in a new country (Crawley 1989; Ehrlich 1989; Williamson 1989, 1996; Gilpin 1990; di Castri 1991; Fryer 1991; Lidicker 1991; Norton et al. 1996; Ricciardi and Rasmussen 1998; Arthington et al. 1999; Enserink 1999). Williamson (1996) concludes that an invader can be any sort of species going into any sort of environment. Some experts believe that current ecological theory on animal invasions is inadequate to make quantitative scientific predictions (Crawley 1986, 1989; Brown 1989; Simberloff 1989). Ehrlich (1989) stated that 'One certainty is that population biologists are still a long way from any comprehensive quantitative theory of what determines the potential for becoming a successful invader'. He suggests that such a theory may not be possible because demographic and environmental stochasticity plays such a large part in any individual introduction that it is not possible to generate mathematical probability distributions of likely success. Nevertheless, he points out that, despite these high levels of uncertainty, what is known is far from trivial, and ecological knowledge can contribute much to assessing the probability of invasion success.

Daehler and Strong (1993) suggest that predictions of invasion risk by exotic species, based on fairly simple risk assessment models including such factors as climate matching or overseas range size and past invasion successes by the species or its close relatives will allow predictions to be made at low-cost to guide management policies. Daehler and Strong (1993) acknowledge that such simple approaches may overestimate the probability of establishment success, but consider their simplicity and low cost will enable large numbers of potential invaders to be screened, whereas more complicated approaches that require intensive, long-term and expensive study of the biology and ecology of introduced species and the structure and function of potentially invaded ecosystems, will preclude the assessment of many species. While acknowledging the potential value of such simple approaches, Lodge (1993c) queried their reliability, because he considered that the characteristics of the community being invaded are as critical to establishment success of an introduced exotic species as the characteristics of the introduced species. However, Moyle and Light (1996a,b) contend that all aquatic systems are invasible regardless of the biota already present, if abiotic conditions are appropriate. If this is true, fairly simple modelling involving climate matching and past history of invasion, should go much of the way to determining the risk of establishment posed by introduced species, at least over broad geographic areas. At more local scales, other components of the abiotic environments, such as water chemistry, depth and flow, and substrate structure are also likely to be significant.

While Erlich's (1989) contention that there is no comprehensive quantitative theory for determining which species will become successful invaders is still essentially true, in the last decade several papers have demonstrated statistically significant links between many of the factors listed in Section 1.2 and establishment success. This information can be used to give probabilistic estimates of whether an exotic species released in Australia is likely to successfully establish. Unfortunately, many of the statistical tests conducted to look for factors that may be correlated with establishment success have lacked power, because sample sizes are often small and because fish species that have been introduced do not necessarily evenly represent the attributes that ecologists want to test. Hence, a significant effect on establishment success will often only be demonstrated for factors that have a fairly major and consistent effect, such as climate match and introduction effort. Where no significant effect has been found for a factor, such as for diet and human commensalism, this does not mean that it does not influence establishment success. Expert opinion, published in the scientific literature, suggests that such factors may well be potentially important and, thus perhaps they should be considered in the qualitative components of risk assessments.

Kolar and Lodge (2002) found that the traits associated with establishment success for exotic fish in the Great Lakes of North America were not the same as the traits associated with rapid spread following establishment. For example, these authors found relatively fast body growth was positively associated with establishment but was negatively associated with quickly spreading species. In addition to slow body growth, Kolar and Lodge (2002) found two other traits associated with quickly spreading fish: poor survival in high water temperatures and toleration of a wider temperature range. Fish do not seem to share traits found for other vertebrate taxa associated with spread. For example, Duncan et al. (2001) and Forsyth et al. (2004) found that exotic birds and mammals that have spread widely in Australia have traits associated with faster population growth rate (including small body size, shorter life span, lower weaning age, short incubation periods, more offspring or broods per year) as well as having larger overseas range sizes and a better climate match than species that have not become widespread. It would appear that traits associated with spread may be taxon specific or location specific although Kolar and Lodge (2002) examined traits associated with rate of spread whereas Duncan et al. (2001) and Forsyth et al. (2004) examined traits associated with extent of spread which could account for the major differences found in these studies.

Section 2: Review of factors affecting the potential impacts of exotic finfish

2.1 Types of impact

The potential impacts of exotic fish can be classified into three main categories (modified from Aquatic Nuisance Species Taskforce 1996):

1. *Environmental impacts* including: ecosystem destabilization, reduced biodiversity, reduced or eliminated keystone species, reduced or eliminated endangered or threatened species; effects of control measures.
2. *Economic impacts* including: reduced agricultural or fisheries productivity or increased production costs; flow-on effects on subsidiary industries; trade effects; damage control costs; injuries to people or domestic animals.
3. *Social and political impacts* including: aesthetic damage; consumer concerns; political repercussions.

The environmental impact of an exotic fish species on a freshwater or estuarine community can be defined as any effect attributable to that exotic that causes, directly or indirectly, changes in the density, distribution, growth characteristics, condition, genetics or behaviour of one or more native populations within that community (modified from Taylor et al. 1984). This definition is independent of human judgements about the benefits or harm of such impacts.

Exotic fish may also have positive impacts, for example, its importance as a biocontrol agent, aquatic pet or display specimen, sport fish, scientific research specimen, or its use in aquaculture (Aquatic Nuisance Species Taskforce 1996).

2.2 Demonstrating impact

A demonstration of environmental impact requires verification of a causal relationship between changes in a native population, a previously introduced exotic population, or in an aquatic community, and the presence of the exotic fish. Rigorous proof of a cause–effect relationship requires an experimental design in which appropriate controls and replications are used. Such experiments have rarely been conducted with the introduction of exotic fish. Less rigorous demonstration of impacts can be obtained by detailed study of a community before and after the introduction of an exotic. Again such research is rare because pre-invasion data sets are usually unavailable and because the introduction of exotic fish often occurs concurrently with other changes which make attribution of cause–effect relationships difficult. For some effects, however, such as predation on native fish by certain exotic piscivores, the timing and magnitude of the impact following the introduction make the existence of a causal relationship highly probable. It is also possible to demonstrate impact following an introduction, by experimentally manipulating densities of the exotic species and monitoring community responses.

The best method for developing a predictive model for the impacts of fish invasions is to compare the outcomes following multiple introductions of a given species in different ecosystems to determine if the effects of the invader are consistent and therefore predictable in different environments (Ricciardi and Rasmussen 1998; Ojaveer et al. 2002; Ricciardi 2003). Where such multiple introductions of the same species into different communities are associated with similar impacts, this can provide strong inferential evidence of causal impacts (Taylor et al. 1984). It would then be possible to look at the attributes of fish with known impacts, to determine any attributes associated with harmful impacts. Unfortunately, for most known fish invaders, insufficient quantitative data on impacts are available to make useful comparisons across ecosystems, and the data that do exist are often confounded with impacts due to other factors (Section 2.3). Further, there are an increasing number of species being introduced to new environments for the first time that thus have no invasion history from which to draw predictive information (Ricciardi 2003).

An alternative approach might be to predict the impact of an introduced species from the invasion history of functionally similar fish (Byers et al. 2002). It is intuitively appealing to assume that closely related species are functionally similarly and will thus have similar impacts. Unfortunately invasion histories indicate that taxonomic similarity is not a consistent predictor of impact potential (Ricciardi 2003). For example, following the near simultaneous introduction of two gobiid fishes into the North American Great Lakes around 1990, populations of the tubenose goby *Proterorhinus marmoratus* remained small and isolated while the round goby *Neogobius melanostromus* spread to three lakes and into the St Lawrence River and its expansion was accompanied by concomitant declines in other fish probably due to predation and competition for food and shelter (Ricciardi 2003). Similarly, brown trout *Salmo trutta* is highly invasive and implicated in many native species declines in several countries whereas the Atlantic salmon *Salmo salar* is a poor coloniser and has rarely been associated with species losses (Welcomme 1988).

2.3 Reliability of evidence

Unfortunately, for most exotic finfish, both in Australia and overseas, reliable knowledge about impacts is sparse for two main reasons. Firstly there has been limited research and in particular there are usually scarce preinvasion data sets (Ojaveer et al. 2002). Secondly, introductions of exotic finfish have often coincided with other changes to freshwater and estuarine habitats which means impacts due to exotic fish are confounded with impacts due to other factors (McKay 1984; Moyle 1986; Welcomme 1988; Moyle and Williams 1990; Crowl et al. 1992; Arthington and Mckenzie 1997; Kailola 2000; Elvira 2001; Ojaveer et al. 2002). These include the following factors:

- changed water flows (for example due to weirs, dams, irrigation or channel straightening)
- reduced water quality (including chemical pollution, modified temperature regimes, turbidity and eutrophication)
- fishing (including collections for aquaria)

- introductions of exotic plants
- disturbance by other introduced animals and people (for example grazing or cropping in water catchments or along banks, clearing of snags and logs).

These factors are often cumulative or complementary and may interact synergistically such that the impact of several factors acting together is greater than the sum of the individual factors acting alone (Elvira 2001). For example, some native fish might survive predation by introduced fish unless habitat disturbance destroys aquatic plants they use for shelter, so they are unable to hide from the predatory fish. Such interaction make it difficult to accurately assign individual causes to specific impacts.

The combined effects of introduced species and human-caused environmental changes may cause rapid and unpredictable changes in fish assemblages (Herbold and Moyle 1986; Meng et al. 1994). For example, in New Zealand, deforestation and swamp drainage have had detrimental impacts on native species. In areas of New Zealand where human population is low, and where deforestation and land development are less than elsewhere, galaxiid stocks and retropinnid smelts remain productive or abundant in spite of the co-occurrence of introduced trout (McDowall 1990).

Many of the impacts attributed to exotic fish are correlative or anecdotal (King 1995). Nonetheless, the diet and behaviour of some finfish definitely gives them the potential to harm native fish and cause other environmental damage in their introduced habitats. This potential combined with measured changes in abundance or distribution of vulnerable native species following their introduction to new habitats, provides compelling evidence of harmful impacts (Moyle 1986). For example, Yang (1996) recorded that 18 exotic fish species have been introduced in Yunnan Province in China and a further 16 species that were not originally present in Yunnan have been translocated from elsewhere in China. Yunnan had 432 documented freshwater fish species, but following the introduction of the exotic and translocated fish many of these native fish have declined or disappeared: 130 of the endemic fish have not been caught for the last five years, a further 150 species that were common are now rare and the remaining 152 species have declined. The introduced fish affect the endemic fish directly by eating their spawn and competing for food and indirectly, by encouraging changed fishing methods that have a greater impact on the native species than previous methods. Although other disturbances have occurred in these habitats, including land reclamation, irrigation works and overfishing, an analysis of the timing of endemic fish declines in relation to the timing of exotic fish introductions and other disturbances, indicated that the introduced fish were the main factor causing declines in the endemic fish (Yang 1996).

2.4 State of knowledge on impacts

According to some ecologists, only about 10% of exotic species become widespread pests following their establishment (Williamson and Brown 1986; Williamson 1996, 1999; Williamson and Fitter 1996; Enserink 1999; Smith et al. 1999). However, a review of the pest status of exotic birds and mammals in Australia and elsewhere suggests that this generalisation is doubtful for vertebrates and that a more realistic figure for exotic mammals and birds is that around 50% become pests (Bomford 2003). It is not possible to estimate a reliable figure for the percentage of exotic fish that become pests because few reliable data on fish impacts are available and hence impacts due to exotic fish are largely under-reported in the scientific literature. However, several studies have attempted to estimate the proportion of exotic fish that have detrimental environmental impacts:

- Maciolek (1984) reviewed fish introductions to Pacific Ocean islands and found 14 of 31 (45%) introduced fish species had substantial impacts on native fauna, either directly or indirectly.
- Welcomme (1988) examined FAO records of 1354 introductions of 237 exotic fish species into 140 countries between 1800 and 1985. He found the introduced species were considered a significant element in their new habitat in 23.7 % of introductions but were only considered to be a serious environmental pest in 6.6 % of introductions.
- Ross (1991) examined 31 studies of the introduction of exotic fish to 26 aquatic systems in Europe, North America, Australia and New Zealand and found 77% of studies reported a decline in native fish numbers following the introduction of exotic or translocated fish. Of the 26 systems studied, 20 reported native fish declines, eight attributed the declines to predation and eight to competition, with no mechanism identified for the other four systems.

Given that the impacts of most introductions will not have been studied, the figures above could be significant underestimates of true impacts. Cassey and Arthington (1999) suggest the low percentage of fish considered to be pests is most likely an artefact of the scale of most studies and that most changes will be subtle effects such as local extinctions, behavioural and evolutionary changes of native species, habitat and environment changes, food web alterations, and transmission of pathogens. Such effects are rarely investigated in detail (Townsend 1991).

2.5 Types of environmental impact and their significance for impact risk assessment:

A review of the literature on exotic finfish introductions indicates the following types of impact may occur. These are briefly described, together with examples and their risk assessment significance.

(i) Competition for resources

Competition can lead to reduced growth rates, survival and recruitment (Taylor et al. 1984; Welcomme 1988; Arthington and Lloyd 1989; Arthington 1989, 1991; Ross 1991; Crowl et al. 1992; Lever 1996; Moyle and Light 1996a,b; Kailola 2000; Ojaveer et al. 2002). Two types of competition may occur, exploitation and interference competition (Pianka 1978).

Exploitation competition occurs when different species use common resources that are in short supply, most commonly food and space, which may lead to displacement of the weaker species to less favourable foods and habitats (niche shifts) and hence cause reduced survival and recruitment (Ross 1991). For example, McIntosh et al. (1992) found that the native fish *Galaxias vulgaris* occurs at much lower densities in the presence of introduced brown trout in New Zealand. Both taxa exhibit considerable dietary overlap, and most competition centres around optimal feeding locations. Similarly in Australia, the diets of *Galaxias olidus* and brown trout *Salmo trutta* overlap and where the species occur in the same waterway, the distribution of the galaxiids is fragmented through interspecific competition for food (Fletcher 1979).

Interference competition occurs when different species seeking a common and abundant resource harm each other in the process, for example, by aggressive behaviour. For example, mosquito fish *Gambusia holbrooki* in Australia compete with native species for resources by fin nipping and aggression towards native fish up to twice their size which can reduce survival and recruitment of the attacked species (Arthington and Lloyd 1989).

Exotic fish are often better adapted to disturbed habitats than native fish which can enhance their competitive advantage in these habitats (Moyle and Light 1996b; Arthington et al. 1999). Arthington (1989, 1991) reviews the impacts of competition between exotic and native freshwater fish in Australia. She suggests that because many exotic fish are generalist feeders that exhibit trophic opportunism, there is considerable potential for competition between native and exotic fish, and there is evidence that this has occurred and caused declines in some native species.

Moyle and Light (1996b) suggest when exotic fish invade constant environments, such as desert springs, tropical lakes or artificial reservoirs, they often have highly adverse effects on native species, because in an unvarying environment it is much easier for a single species or group of species to become dominant. In contrast, in a fluctuating environment with varying resource types and availability, no one species or group of species can stay dominant for an extended period.

In general there has been insufficient research to determine the extent to which competition from exotic fish has detrimentally affected native fish. According to Herbold and Moyle (1986) and Moyle et al. (1986), introduced fish do not fill ‘vacant niches’. Rather, they compress the realised niches of one or more of the species already present, possibly to the point where pre-existing species are eliminated.

Risk assessment significance: Competition by exotic fish has the potential to be highly detrimental to native species but scientific knowledge is currently inadequate to allow reliable predictions about which exotic species will have the worst impacts when they are introduced to new environments. Elvira (2001) says species associated with high impacts tend to have a broad diet whereas introduced fish having low impacts are characterised by specialized diet, hence generalist feeders may have more potential to have competitive impacts than specialist feeders.

(ii) Predation

Predation leads to reduced survival rates of prey species (Taylor et al. 1984; Arthington 1989, 1991; Crowl et al. 1992; Lever 1996; Moyle and Light 1996a,b; Kailola 2000). For example, predatory Nile perch were introduced to Lake Victoria and other similar lakes in Africa where they caused the loss of many native cichlid species (Welcomme 1988). In Australia mosquito fish *Gambusia holbrooki* attack and eat juvenile fish and may eat fish fry (Arthington and Lloyd 1989; Kailola 2000). Predation by mosquito fish may contribute to declines in native fish populations in Australia including populations of rainbowfish *Rhadinocentrus ornatus, Hypseleotris galli*, *Melanotaenia fluviatilis*, *Galaxias occidentalis*, nightfish *Bostockia porosa*, westralian pygmy perch *Edelia vittata*, gudgeons *Mogurnda* spp, glassy perch *Ambassis* spp, rainbowfish *Melanotaenia* spp, blue-eyes *Pseudomugil* spp, hardyheads *Craterocephalus* spp and smelt *Retropinna* sp (Arthington et al. 1983 and 1999; Arthington and Lloyd 1989; Lloyd 1990; Ivantsoff and Aarn 1999). Arthington and Marshall (1999) consider that the capacity of mosquito fish to feed opportunistically on a wide variety of aquatic prey, its consumption of fish eggs and larvae and its aggressiveness towards other fish species, could certainly exert significant pressure on small populations of indigenous fish themselves already under threat from habitat loss and water pollution.

Many smaller carnivorous fish species prey on juvenile fish and some cyprinodonts, particularly *Gambusia* spp may feed on the eggs of other taxa (Welcomme 1988). For example, tadpoles of native frog species in Australia are highly susceptible to predation by *Gambusia holbrooki* and hence this species may contribute to declining frog populations (Morgan and Buttemer 1996; Webb and Joss 1997; Kailola 2000).

According to Crowl et al. (1992), many Australian endemic species are likely to have evolved in relative isolation from aggressive predatory fish and hence are particularly prone to negative impacts from novel predators. For example, Crowl et al. (1992) suggest the family Galaxiidae, found only in the southern hemisphere, have little co-evolutionary history with predators. According to Arthington et al. (1999), isolated aquatic communities are particularly at risk form introduced predators, and piscivores may pose a particularly high risk.

Piscivores may be more likely to alter invaded communities than fish from other dietary groups. Moyle and Light (1996b) consider a relatively small number of invasive fish species, mainly piscivores, are responsible for most recorded cases of invading fish causing extinctions of native fish. Many of these predatory fish were introduced intentionally for sport fisheries.

Risk assessment significance: Predation by exotic fish has the potential to be highly detrimental to native species. Piscivores may be more likely to alter invaded communities than fish from other dietary groups. Piscivores are responsible for most recorded cases of introduced fish causing extinctions of native fish.

(iii) Habitat disturbance and food web effects

Habitat alterations occur when introduced fish change the habitat of resident species, often through their feeding behaviour (Taylor et al.1984; Arthington 1989, 1991; Crowl et al. 1992; Lever 1996; Townsend 1996; Kailola 2000; Elvira 2001; Ojaveer et al. 2002). The most common effects are the displacement of aquatic vegetation and the degradation of water quality. Herbivorous fish eat plants and plants can also be uprooted through digging for food or nesting sites (Taylor et al.1984; Elvira 2001). This can change complex habitats into simple ones (Crowl et al. 1992). Reductions in macrophytes can also cause increases in turbidity through wave mediated erosion and continual mixing of silt previously stabilised by rooted plants. Turbidity can also be caused by introduced fish through roiling of shallow littoral zones by bottom feeding species such as European carp, and by nesting and spawning activities, especially by species that form dense aggregations for breeding (Taylor et al.1984). Increased turbidity can have detrimental effects on native species by disrupting breeding and reducing recruitment, slowing growth or interfering with normal respiratory and secretory functions (Taylor et al.1984).

Grass carp *Ctenopharyngodon idella* in Donghu Lake, China, caused the virtual disappearance of submerged macrophytes and dramatic blooms of planktonic algae. These conditions favoured silver carp and bighead carp, also native to China but not to Donghu Lake. Most of the 50 endemic fish species in the lake disappeared and the number of benthic invertebrate species fell from 113 to 26 and zooplankton species fell from 203 to 171 (Kottelat and Whitten 1996).

Such alterations in ecosystem structure can have flow-on effects to oxygen levels, turbidity, and nutrient cycling, and hence change community assemblages. Bottom-feeding fish, such as cyprinids, transfer nutrients from sediment into the water by excretion, which can contribute to formation of algal blooms (King 1995). In contrast, Australian native fish feed largely within the water column and so do not recycle sediment nutrients (Kailola 2000). Introduced species can also become prey for larger fish, thus changing food availability (Taylor et al.1984; Ross 1991).

Large secondary effects can also result from introductions of predatory fish and these flow-on effects are usually hard to predict (Li and Moyle 1981; Townsend 1991). For example, lake and pond ecosystems are strongly influenced by the feeding behaviour and population dynamics of predatory fish, such as trout and *Gambusia* spp (Hurlbert et al. 1972; Townsend, 1996). Top-level predators can reduce the number of grazing fish and zooplanktivores and large grazing invertebrates, and the extent and efficiency of their grazing, so permitting an increase in phytoplankton and even causing algal blooms. For example, Moyle and Light (1996b) cite many ‘well documented’ case histories of ‘dramatic effects of piscivores on fish assemblages in lakes and streams’. Moyle and Light (1996b) say ‘the effects of a predator invasion can “cascade” through an entire ecosystem, altering fundamental ecosystem processes’.

In addition to their direct effects on survival by removing fish by hunting and aggression, predators can also influence community structures by altering the balance of interspecific competition and hence could alter species diversity in the communities where they are introduced (Ross 1991). Exotic predators can profoundly affect the population dynamics of native prey species (Elvira 2001).

The presence of exotic fish may significantly increase the amount of prey available to native predators (Taylor et al.1984; Elvira 2001). For example, the introduced round goby may cause relaxation of predation pressure on several native fish in the Baltic Sea, such as sand eel *Ammodytes tobianus* and sprat *Sprattus sprattus* by being more favourable food for most abundant piscivores than these native prey species (Ojaveer et al. 2002).

Based on their assessment of fish invasions in Californian streams, lakes and estuaries and in wet zone streams of Sri Lanka (Wikramanayake and Moyle 1989), Moyle and Light (1996b) concluded that detritivores and omnivores are less likely to have harmful affects on fish assemblages in invaded freshwater communities than fish from other dietary groups. However, although they may not eliminate native finfish, detritivores and omnivores may still considerably alter ecosystem functioning (Power 1990; Moyle and Light 1996a,b) and hence may possibly cause extinctions of lower order taxa.

Risk assessment significance: The secondary or flow-on effects in food webs are the least studied and most difficult effects of exotic fish introductions to predict. Exotic fish have the potential to have detrimental effects on recipient ecosystems when they alter the habitat of native species. Species that destroy or modify aquatic vegetation or that stir up sediments to increase turbidity possibly have the highest impacts, but introduced piscivores may also significantly alter community structures. Detritivores and omnivores may be less likely to have harmful affects on fish assemblages.

(iv) Potential to cause injuries

The following attributes give fish the potential for causing injury (modified from McKay 1984):

- strong, serrated or venemous spines that lock into position (most freshwater catfishes)
- electric organs (for example electric eels and catfish)
- poisonous flesh (for example fish in the genus *Tetraodon*)
- sharp teeth capable of cutting flesh (for example piranhas *Serrasalmus* spp)

For example, the electric eel is potentially dangerous to all animals, including aquatic organisms and land-dwelling animals. These eels transmit direction-finding pulses at a frequency of 50 Hz and are capable of producing shocks reaching one ampere and 600 volts. Fish and mammals as large as horses may be paralysed by it (Department of Primary Industries and Fisheries 2004).

Risk assessment significance: Fish that cause injuries elsewhere in their range may be expected to have similar effects if they are introduced to Australia.

(v) Role as disease carriers and reservoirs

Diseases spread from exotic fish to native fish may have huge ecological consequences (Hoffman and Schubert 1984; Shotts and Gratzek 1984; Taylor et al. 1984; Langdon 1990; Arthington 1991; Lever 1996; Kailola 2000; Elvira 2001). This may include diseases caused by viruses, bacteria, protozoa, fungi and parasites. Little is known about diseases and parasites associated with aquarium fish (McKay 1984).

Risk assessment significance: It is difficult to predict the role exotic species may have as vectors or reservoirs of diseases or parasites in new environments. However, species that harbour or transmit diseases or parasites elsewhere may transmit the same or similar diseases or parasites if these are present in Australia.

(vi) Hybridisation with native species and other genetic changes

When exotic fish hybridise with native fish, and produce fertile offspring, this corrupts the gene pool of the native fish and hence may pose a threat to their survival (Taylor et al.1984; Arthington 1989, 1991; Crowl et al. 1992; Lever 1996; Williamson 1996; Arthington and McKenzie 1997; Elvira 2001).

Fish are generally more plastic in their potential for hybridising than are mammals and fewer crosses between fish species result in sterile progeny (Welcomme 1988). Hybrids may be produced spontaneously and survive in the wild. Through the removal of geographic barriers that normally prevent mixing of taxa, or under the pressures exerted through introductions that can change normal behaviour patterns, hybrids arise between species or genera that would not otherwise interbreed (Elvira 2001). For example, the marbled trout *Salmo marmoratus*, is endemic to rivers in the Adriatic Basin in Europe. Brown trout were stocked there in 1906 and this has led to hybridisation between the two species and the marbled trout largely disappearing (Elvira 2001). Maciolek (1984) reported crosses between *Micropterus salmoides* and *Lepomis macrochirus* in at least two Hawaiian reservoirs.

According to Kailola (1989), if rainbowfish (Melanotaeniidae) were introduced to Australia from New Guinea, they might hybridise with Australian native species. Williamson (1996) reported negative effects have been recorded in all known cases of hybridisation between introduced freshwater fish and native species.

Some ecologists have suggested fish taxa that freely hybridise in the wild (such as cichlids) may produce fertile hybrids that are a greater threat as pest species than the parent stock because of hybrid vigour and enhanced reproductive potential (Kailola 2000). However this theory is untested.

Exotic fish can have genetic effects other than hybridisation. Changes in the genetic structure of a population can occur due to reductions in size, reduced numbers of subpopulations or phenotypes, due to competition, habitat alterations or predations (Elvira 2001).

Risk assessment significance: Exotic species that have close relatives among Australia's endemic fish could hybridise with these native species and corrupt their gene pool.

2.6 Other factors from the literature which have been suggested as having potential value for assessing the risk of impacts by introduced exotic fish

(i) History of being a pest overseas

Fish which are pests overseas may well become pests if they establish in Australia. Simple predictions can be made by assuming that invaders will cause significant impacts in a new area they have established if they have already done so in other regions (Townsend and Winterbourn 1992; Ricciardi and Rasmussen 1998). While correlative analyses are often limited by a scarce amount of comparable quantitative data, they can give an indication of potential impacts (Ricciardi and Rasmussen 1998). However, a species' history of impacts elsewhere is not an infallible guide to its potential impact in Australia. There are many examples in the scientific literature of species that have developed new behaviour and new dietary preferences when introduced to new environments and hence had impacts that could not have been predicted from their history. Hence species that have little harmful effects in their native (or previously introduced) range may have devastating effects when introduced to a new country (Bomford 2003; Hayes and Sliwa 2003). A further problem is that many potential pest species may not have been introduced outside their natural range yet, and so have not had the opportunity to demonstrate their pest potential.

Risk assessment significance: Descriptive information on the impacts of previous invasions may provide a basis for useful predictions, although with a high degree of uncertainty. A precautionary approach is advisable for fish species which have no history of establishing outside their natural range.

(ii) Rate of spread

Species that spread rapidly from their initial place of establishment are likely to be harder to eradicate, contain or control, and are more likely to become widespread and to be considered pests, than species with a slow rate of spread. The factors that influence the rate of spread, and the final geographic range of an exotic species established in a new environment may differ from the factors that influence the probability of the initial establishment (Duncan et al. 2001; Kolar and Lodge 2002; Forsyth et al. 2004). Kolar and Lodge (2002) found exotic fish which spread rapidly in the Great Lakes of North America had slower growth rates, poorer survival in high water temperatures and tolerated a wider temperature range than slowly spreading fish.

Risk assessment significance: There are inadequate data on rates of spread to enable this factor to be used to predict the pest potential of future fish introductions to Australia. However, fish that are known to have spread rapidly following their release into new environments overseas should be considered to pose a high risk.

(iii) Socio-economic effects

While significant recreational and commercial fisheries have developed from introduced fish such as trout, exotic fish species not favoured for human consumption can replace popular commercial or recreational fishing species (Welcomme 1988; Lever 1996; Elvira 2001). For example, the Mozambique tilapia established in reservoirs in India where they replaced more favoured native species such as some native carp species (Welcomme 1988; Lever 1996). Nile perch introduced to Lake Victoria in Africa destroyed pre-existing sustainable fishing for a range of native species and according to Fryer (1991) it is doubtful if current levels of fishing for Nile perch are sustainable or provide equivalent benefits and levels of employment for local people compared to pre-existing fisheries.

European carp introduced to Australia are claimed to cause problems eroding banks of irrigation channels and blocking irrigation machinery and to have had detrimental impacts on some native species that are used for recreational and commercial fishing but reliable data on these effects are unavailable (Koehn et al. 2000).

Risk assessment significance: Introduced fish may bring economic benefits or cause economic harm. Because the distribution, abundance, sustainable harvest levels and impacts on other fish species of introduced fish are hard to predict accurately, forecasting the economic consequences of fish introductions to Australia is difficult. An examination of the economic consequences of previous introduction of a species elsewhere in the world may provide some indication of potential economic consequences if a given species was introduced to Australia.

(iv) Similar appearance to harmful species

If a species could be readily confused with undesirable or prohibited fish species at the size it is imported, this could facilitate accidental importation of the harmful species (Kailola 1989). For example, small piranha *Serrasalmus* spp might be illegally imported in bags containing large numbers of the silver dollar *Metynnis* sp (McKay 1984).

Risk assessment significance: The risk of accidental entry of unwanted species through ports of entry will be determined by the adequacy of resources and expertise of quarantine authorities at these ports. In the future it may be possible to undertake DNA testing of fish proposed for import at reasonable cost with tests now being developed for commercial use (pers. comm., Dr Nic Bax, 2004).

(v) Taxa

Kailola (2000) categorised the exotic fish families present in Australia taxa according to the level of risk they posed to native fish species and the environment. She considered the highest risk taxa were Poeciliids and Cyprinids, followed by Salmonids, Percids, Cichlids (moderate risk), and Cobitids and Belontiids (least risk). Kailola (2000) presented considerable anecdotal evidence on the impact of the fish taxa she assessed although she considered there was insufficient information about the latter three taxa to fully assess risk. Also, her review was restricted to exotic fish taxa already present in Australia. There are many other taxa with a record of having significant detrimental impacts on native species, including extinctions, where they are introduced, for example:

- round goby (family Gobiidae), a piscivore (Ricciardi 2003)
- goby *Glossogobius giuris* (family Gobiidae), a piscivore that also feeds on small insects and crustaceans (De Silva 1989)
- *Neosalanx taihuensis* (family Salangidae), a filter feeder that competes for food (Yang 1996)
- Nile perch (family Centropomidae), a piscivore (Welcomme 1988).

Risk assessment significance: A detailed review of the literature on impacts of exotic fish worldwide might enable a ranking by taxa of risk of environmental (and economic and social) impacts. However, a species' history of impacts elsewhere is not an infallible guide to its potential impact in Australia (see Section 2.6i). Such a review was beyond the scope of the current project.

(vi) Abundance

Elvira (2001) suggests fish species associated with high impacts tend to have abundant populations in their native habitats.

Risk assessment significance: Few data are available on fish abundance and fish in new habitats can reach densities much higher than those in their natural range. therefore this factor is not considered to be of value for predicting risk of impact.

(vi) Other factors

Kolar and Lodge (2002) found exotic fish which were considered to be a nuisance (pest) in the Great Lakes of North America had smaller eggs, wider salinity tolerances, and better survival in low water temperatures than non-nuisance fish. Kolar and Lodge (2002) found that these factors correlated with nuisance status differed from the factors they found were correlated with establishment success (Section 1.3). However, Fishbase (2004) lists 27 exotic fish species that have been reported to have adverse ecological impacts in their introduced range, and an assessment of these 27 species (Appendix H, Table H1) indicates all except one of these species have attributes that are correlated with high establishment success for fish species introduced to Australia.

Risk assessment significance: Fish that are considered to be environmental pests have attributes that give them a high risk of establishing exotic populations in Australia.

2.7 Discussion

Unfortunately, relatively little research has been conducted on the impacts of exotic fish. Except for obvious species extinctions or economic losses, few studies have examined the possible suite of community changes that an invasive species can have (Cassey and Arthington 1999). European carp and *Gambusia* spp (to a much lesser extent) are exceptions. As only two of the exotic finfish species established in Australia can be assessed for impact, Kailola (2000) considered that neither meaningful categories nor comparisons can be made. According to Elvira (2001) there are too few data to demonstrate how introduced species affect native species and thus it is not possible to make rational decisions about which species are safe to import because they pose a low risk of harm.

The impacts of exotic fish are most readily recognized when an abundant introduced species leads to major declines in native fish species or causes obvious habitat alterations. Less obvious and less studied impacts include competitive interactions that limit resource availability to native species, changes to food web structures, genetic alterations and changes in abundance of lower order taxa and lower trophic level species. Defining harmful species and identifying species that cause or can potentially cause ecological harm is inevitably a subjective process (Hayes and Sliwa 2003). Ecological harm is difficult to define and evaluate when it refers to species that are of no direct economic value or to impacts on community structures and ecosystem processes. Such impacts are time consuming and hence expensive to evaluate, are often hampered by a lack of pre-invasion data, and therefore are largely under-reported in the scientific literature. Hence some exotic species are perceived as having little obvious impact. There is no universally agreed formula to measure the environmental harm caused by introduced species and hence opinions on the type, extent and significance of impacts vary and even conflict (Hayes and Sliwa 2003).

Moyle and Light (1996b) suggest most successful invasions by exotic fish do not have major community effects on recipient ecosystems, and that where such effects do occur, they are generally observed where species richness is low. However, these observations may simply be because in more diverse communities, impacts are less obvious, or may take longer to occur (Moyle and Light 1996b). Also there are exceptions to this generalisation, such as in Lake Victoria, Africa where the introduced piscivorous Nile perch eliminated over 200 species of endemic haplochromine cichlids (Welcomme 1988). Similarly, a goby, *Glossogobius giuris*, caused the extinction of 17 endemic cyprinid species in Lake Lanao, Philippines (De Silva 1989: 146). Hence Moyle and Light's (1996b) generalisation should not be used as grounds for assuming that most fish introductions in diverse communities will not have adverse ecological effects. As a general rule it is best to assume we know too little about which communities are most vulnerable and that interactions are too complex for this to be useful predictive approach for risk assessment.

Many exotic fish initially establish in highly disturbed and polluted habitats, often in or around urban areas. While such habitats are probably so degraded that they retain few native biota of conservation significance, exotic species that establish in these environments, may act as sources for eventual spread to other habitats where they have the potential to be a much higher threat to native species.

Since Australian aquatic systems are inherently different from overseas ones, there are limits to the extent to which conclusions about impacts drawn from overseas studies can be extrapolated to Australian conditions (King 1995). Australian freshwater systems differ markedly from those overseas. Not only is Australia one of the driest continents in the world, but Australian river flows are among the most variable. Australian waters also differ chemically from many other countries with most water bodies being more saline and turbid than overseas examples. Biological differences are also significant with peak litter fall in Australia occurring in summer instead of the Northern Hemisphere autumn, and the Australian litter being mainly coarse woody material (King 1995). These differences could all affect the impacts of introduced fish.

Fish may show adaptive changes following colonisation events to better suit them to their new environment and Arthington (1991) reviews several examples. Shifts in thermal tolerance have been recorded for several species, including *Gambusia holbrooki* and rainbow trout *Oncorhynchus mykiss*. Hybridisation between different strains of introduced species can lead to new genetic strains that are more invasive or have higher pest potential than the parent strains. An example is the Boolara strain of European carp in Australia (Koehn et al. 2000).

Moyle (1986), Moyle and Williams (1990) and Moyle and Light (1996a) suggest that native fish are most typically extirpated from waters that have been heavily modified by human activity, where native fish assemblages have already been depleted, disrupted or stressed. These authors recognise that exotic fish can establish in undisturbed areas, but consider the native fish in such systems are usually able to adjust to the invader and extinctions following invasions of undisturbed systems are rare (Moyle and Light 1996a). However, they suggest that exceptions to this generalisation may occur when the introduced fish is a piscivores or when it is capable of hybridising with the resident native species. This theory requires more study before it can be confirmed.

2.8 Conclusions

There is insufficient reliable knowledge of the factors correlated with impacts of exotic fish to make the development of a quantitative model feasible for assessing the risks of impact for new species of exotic fish in Australia. Nonetheless, the review of factors associated with adverse impacts above indicates that the following attributes/factors may increase risk, (with the caveat that fish with an absence of these factors cannot be taken to indicate that there is a low risk of harm):

- adverse impacts elsewhere
- close relatives with similar behavioural and ecological strategies have adverse impacts elsewhere
- generalist feeders
- piscivorous
- destroy or modify aquatic vegetation or that stir up sediments to increase turbidity which may cause the most habitat disturbance
- potential to cause physical injury
- harbour or transmit diseases or parasites that are present in Australia
- have close relatives among Australia's endemic fish
- known to have spread rapidly following their release into new environments.

This list could be used as a checklist to make a qualitative assessment of the threat of impacts posed by the establishment of new exotic fish species in Australia. This would be particularly desirable if decisions are being made on whether to import species of exotic fish that score a moderate or higher risk of establishment in the quantitative risk assessment model developed in Section 3.

Section 3 Simple model to discriminate between exotic finfish species successfully or unsuccessfully introduced to Australia

Aim

To develop a simple quantitative model to predict risk of establishment of exotic freshwater or estuarine finfish introduced to Australia based on an analysis of previous exotic finfish introductions.

Section 1.2.1 of this report demonstrates that there are five key factors associated with the establishment success of exotic fish in Australia:

(i) Number of release events

(ii) Climate match

(iii) History of establishing exotic populations elsewhere

(iv) Overseas geographic range size

(v) Taxonomic group

Factor (i) means that the risk of new exotic fish species establishing in Australia can be expected to increase as the number of people keeping exotic fish increases and the numbers of different fish species kept in collections increases. This is because, as more people keep fish, the number of escapes and releases of new fish species is also likely to increase, and establishment of exotic fish is closely correlated with the number of release events. This risk can be reduced by restricting the import and keeping of fish species which are ranked highly against the other four factors. The model developed in this section provides a simple quantitative method for ranking fish against these four factors:

- Score A is an index of factor (ii): climate match
- Score B uses the number of occurrence records in Fishbase as an index of factor (iv): overseas geographic range size
- Scores C and D are indices of factor (iii): history of establishing exotic populations elsewhere
- Score E is an index of factor (v): taxonomic group.

The following five scores (Scores A–E) all contribute to establishment risk: higher scores = higher risk.

Score A (Climate match score to Australia 0–8):

Climate match = 20(number of squares within 10% of the mean ie highest match) + 10(20% of mean) + 5(30% of mean) + 2(20% of mean) + 1(50% of mean).

Climate matches are calculated in CLIMATE from species distributions in Fishbase (2004) excluding Australian ranges.

Score A:

0: ≤ 11

1: 10 – 100

2: 101– 200

3: 201–500

4: 501–1000

5: 1001– 2500

6: 2501–3000

7: 3001–4000

8: ≥4001

Score B (Overseas range score 0–4):

Number of 1° latitude by 1° longitude grid squares in which an occurrence of the species is recorded in Fishbase (2004) excluding Australia.

Score B:

0: ≤ 5

1: 5–10

2: 11–20

3: 21–30

4: ≥ 31

Score C (Establishment score 0–3):

Locations where successful introductions of the species have occurred excluding Australia – from Fishbase (2004). Where there are no recorded introductions, a moderate risk ranking is given, although a precautionary approach could warrant a higher risk score being given.

Score C:

0: Introduced but never established

1: Never introduced

2: Only established exotic population(s) on island(s) or on one continent (from choice of five continents not including Australia: Africa; Europe; Asia; North and Central America; or South America)

3: Established exotic populations on more than one continent (excluding Australia).

Score D (Introduction success score 0–4):

The number of known successful introductions of the species worldwide expressed as a proportion of the total number of introductions – from Fishbase (2004) excluding Australia. Where there are no recorded introductions, a moderate risk ranking is given, although a precautionary approach could warrant a higher risk score being given.

Score D:

0: Introduced but success rate = 0

1: Success rate of >0 ≤ 0.25

2: Success rate of >0.25 ≤ 0.5

OR

Never introduced

3: Success rate of >0.5 ≤ 0.75

4: Success rate of >0.75 ≤ 1.0

Score E (Taxa risk score 0–5)

Success rates for worldwide introductions of the family or genus of the species being assessed.

Genus risk score: The genus risk score is used as the taxa risk score when number introduction events of all species within the same genus as the species being assessed ≥ 4.

Genus risk score based on proportion of successful introductions (number of successful introductions/total number of introductions) recorded worldwide for all species within the same genus as the species being assessed.

Score E:

0 = Very low: Success rate = 0%

1 = Low: Success rate >0%<10

2 = Moderate: Success rate 10%–25%

3 = High: Success rate >25%<40%

4 = Very high: Success rate 40%–60%

5 = Extreme: Success rate >60%

Family risk score: The family risk score is used as the taxa risk score when number of introduction events of all species within the same genus as the species being assessed = 0–3, to increase the sample size.

Family risk score based on proportion of successful introductions (number of successful introductions/total number of introductions) recorded worldwide for all species within the same family as the species being assessed. Where there are no recorded introductions, or where sample sizes are small, a moderate (or more moderate) risk ranking is given, although a precautionary approach could warrant a higher risk scores being given.

Score E:

0 = Very low:	Success rate = 0% (number introductions ≥ 3)
1 = Low:	Success rate = 0% (number introductions 1–2)
2 = Moderate:	Success rate = 1–25% (any number introductions) OR Never introduced (number introductions 0)
3 = High:	Success rate >25%–60% (any number introductions)
4 = Very high:	Success rate >60% (number introductions 1–2)
5 = Extreme:	Success rate >60% (number introductions ≥ 3)

Scoring for risk assessment:

Establishment Risk Score = Score A + Score B + Score C + Score D + Score E. (Establishment Risk Score values = 0–24)

Establishment Risk Rankings (very low–extreme) are calculated from Establishment Risk Scores based on the score ranges presented in Table 3, Column 2.

Scores A–E values and Establishment Risk Score values for exotic finfish species introduced to Australia are presented in Figures 2 and 3 and Tables 4 and 5.

Table 3. Establishment risk score ranges and numbers of fish introduced to Australia in each Establishment Risk Rank.

Establishment Risk Rank	**Establishment Risk Score ranges***	**Number of finfish species introduced to Australia**		**Number of aquarium fish species introduced to Australia**	
		Successfully introduced	Unsuccessfully introduced	Successfully introduced	Unsuccessfully introduced
Very low	0–6	0	2	0	1
Low	7–8	1	5	1	2
Moderate	9–11	3	6	2	4
High	12–17	10	3	8	2
Very high	18–20	9	2	6	2
Extreme	21–24	8	0	5	0

*The threshold scores for these Establishment Risk Score ranges were selected to maximise discrimination between successfully and unsuccessfully introduced exotic finfish in Australia.

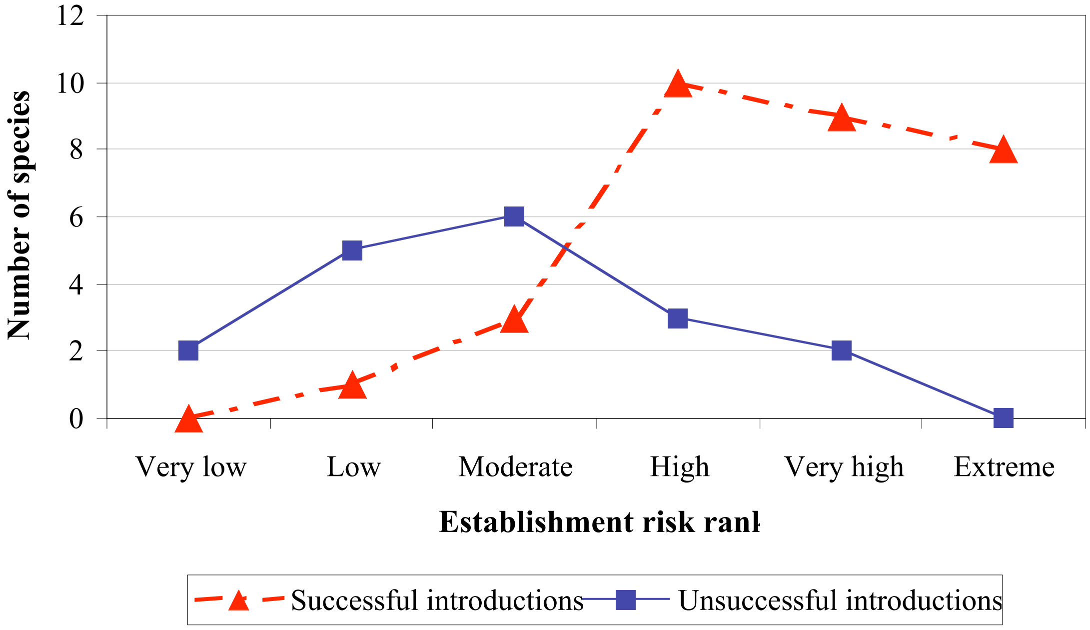

Figure 2: Establishment risk ranks for exotic finfish successfully and unsuccessfully introduced to Australia.

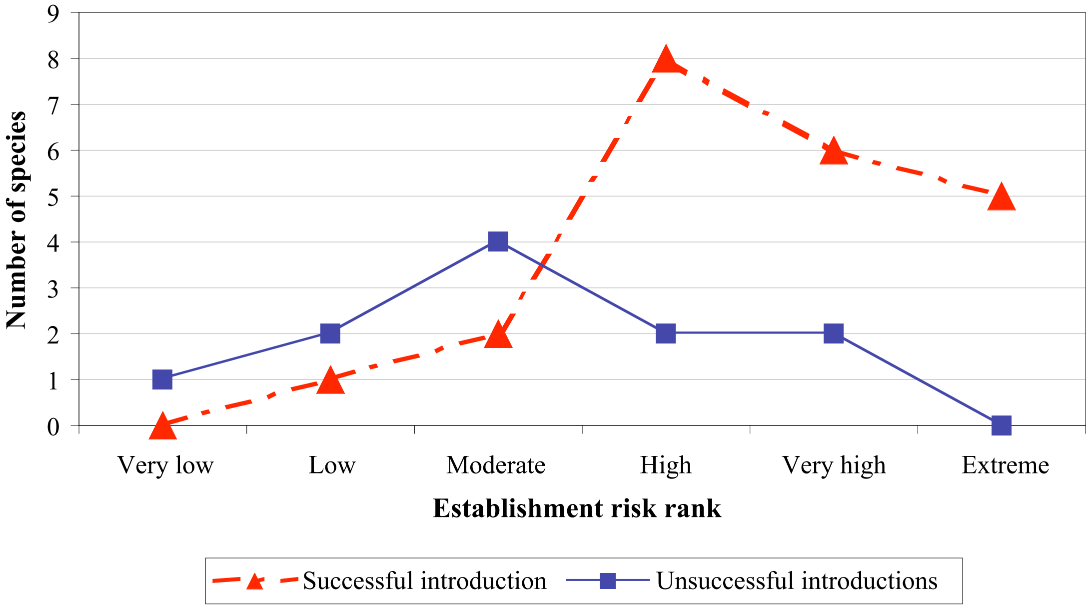

Figure 3: Establishment risk ranks for exotic aquarium finfish successfully and unsuccessfully introduced to Australia.

Table 4. Establishment risk scores for exotic finfish species introduced to Australia. A. Successfully introduced. B. Unsuccessfully introduced (recorded but not known to be established). The data from which scores A–E are calculated were all obtained from Fishbase (2004) which does not include records from the entire geographic range of many species. If more complete data were available, many species could have higher scores. The total score is the sum of the scores in columns A–E. Establishment Risk Ranks are calculated from conversions presented in Table 3.

A. Successfully introduced species[1]	**A**	**B**	**C**	**D**	**E**	**F**	**G**
	Climate match score 0–8	Overseas range score 0–4	Establish-ment score 0–3	Introduction success score 0–4	Taxa risk score 0–5	Total score 0–24	Establishment Risk Rank
European carp *Cyprinus carpio*	7	4	3	4	5	23	Extreme
Tench *Tinca tinca*	6	3	3	4	5	21	Extreme
Goldfish *Carassius auratus*	5	4	3	4	5	21	Extreme
Roach *Rutilus rutilus*	4	4	3	4	3	18	Very high
White-cloud mountain minnow *Tanichthys albonubes*[2]	1	4	2	4	3	14	High
Mosquitofish *Gambusia holbrooki + affinis*[2]	8	4	3	4	5	24	Extreme
Guppy *Poecilia reticulata*	5	4	3	4	5	21	Extreme
One-spot live bearer *Phalloceros caudimaculatus*	3	3	2	4	5	17	High
Sailfin molly *Poecilia latipinna*	5	2	3	4	5	19	Very high
Platy *Xiphophorus maculatus*	4	2	3	4	5	18	Very high
Green swordtail *Xiphophorus hellerii*	5	1	3	4	5	18	Very high
Mozambique tilapia *Oreochromis mossambicus*	8	4	3	4	4	23	Extreme
Red devil/Midas cichlid *Amphilophus citrinellus*	1	2	2	4	3	12	High
Three-spot cichlid *Cichlasoma trimaculatum*	4	2	0	0	4	10	Moderate
Victoria Burton’s haplochromine *Haplochromis burtoni*	2	0	1	2	3	8	Low
Niger cichlid *Tilapia mariae*	1	3	2	4	4	14	High
Oscar *Astronotus ocellatus*	3	4	3	4	5	19	Very high
Blue acara *Aequidens pulcher*[3]	1	2	2	2	3	10	Moderate
Convict cichlid *iatus Archocentrus nigrofasciatus*[3]	4	0	2	4	4	14	High
Jewel cichlid *Hemichromis bimaculatus*[3]	5	3	2	4	5	19	Very high

Table 4 cont.

Redbelly tilapia *Tilapia zillii*[3]	4	4	3	3	4	18	Very high
Jack Dempsey *Cichlasoma octofasciatum* [5]	4	2	3	4	4	17	High
Weather loach *Misgurnus anguillicaudatus*	2	2	3	4	5	16	High
Redfin perch *Perca fluviatilis*	4	3	3	4	5	19	Very high
Rainbow trout *Oncorhynchus mykiss*	8	4	3	4	3	22	Extreme
Brown trout *Salmo trutta*	5	4	3	4	4	20	Very high
Brook trout *Salvelinus fontinalis*	1	4	3	3	4	15	High
Three-spot gourami *Trichogaster trichopterus*	5	4	3	4	5	21	Extreme
Yellowfin goby *Acanthogobius flavimanus*[3,4]	1	1	2	4	5	13	High
Goby *Acentrogobius pflaumii*[3,4]	1	0	1	2	5	9	Moderate
Chameleon goby *Tridentiger trigonocephalus*[4, 6]	3	1	2	4	5	15	High
Average for successful species (standard deviation)	**3.9 (2.2)**	**2.7 (1.4)**	**2.5 (0.77)**	**3.6 (0.92)**	**4.4 (0.8)**	**17.0 (4.3)**	

[1] Listed by in Kailola (2000) as 'established' unless otherwise indicated.

[2] Although *Gambusia affinis* and *G. holbrooki* are now recognized as separate species, with only *G. holbrooki* known to be established in Australia, *G. holbrooki* was once considered to be a sub-species of *G. affinis* and it is clear that Fishbase records do not accurately separate the two taxa according to their current classification.

[3] Listed by Mark Lintermans (in prep.) as 'established' in Australia.

[4] Gobies that probably entered Australia via ballast water (Mark Lintermans pers. comm. 19 April 2004).

[5] Listed by Mark Lintermans (pers. comm. 8 April 2004) as 'established' in Australia.

[6] Listed by Howard Gill (pers. comm. 15 April 2004) as 'established' in Australia.

Table 4 cont.

B. Unsuccessfully introduced species[1] **(recorded but not known to be established)**	**A** Climate match score 0–8	**B** Overseas range score 0–4	**C** Establish -ment score 0–3	**D** Introduction success score 0–4	**E** Taxa risk score 0–5	**F** Total score 0–24	**G** Establishment Risk Rank
Rosy barb *Puntius conchonius*	5	3	3	4	5	20	Very high
Sumatra barb *Puntius tetrazona*	0	0	3	3	5	11	Moderate
Dominican gambusia *Gambusia dominicensis*[4,5]	1	0	1	2	5	9	Moderate
Green terror *Aequidens rivulatus*	1	1	1	2	3	8	Low
Firemouth cichlid *Thorichtys meeki*	4	0	3	4	4	15	High
Banded cichlid *Heros severus*	2	2	0	0	4	8	Low
Redhead *Vieja synspila*	0	4	1	2	4	11	Moderate
Pearl cichlid *Geophagus brasiliensis*	2	1	0	0	3	6	Very low
Blue tilapia *Oreochromis aureus*[2]	4	3	3	4	4	18	Very high
Wami tilapia *Oreochromis urolepis*[3]	4	1	3	4	4	16	High
Chinook salmon *Oncorhynchus tshawytscha*	1	4	2	1	3	11	Moderate
Atlantic salmon *Salmo salar*	5	4	3	1	4	17	High
Plainfin frogfish *Porichthys notatus*	2	4	1	2	2	11	Moderate
Japanese seabass *Lateolabrax japonicus*	2	2	1	2	0	7	Low
Sobaity seabream *Sparidentex hasta*	0	0	1	2	2	5	Very low
Common triplefin *Forsterygion lapillum*	3	0	1	2	2	8	Low
Redbanded perch *Hypoplectrodes huntii*	3	0	1	2	2	8	Low
American flagfish *Jordanella floridae*[4]	1	0	1	2	5	9	Moderate
Average for unsuccessful species (standard deviation)	**2.2 (1.7)**	**1.6 (1.6)**	**1.6 (1.1)**	**2.2 (1.2)**	**3.4 (1.4)**	**11.0 (4.4)**	

[1] Listed by in Kailola (2000) as 'recorded' but not known to be established, or only maintained by repeated artificial releases, unless otherwise indicated below.

[2] Listed by Lever (1996) as 'recorded' in Australia.

[3] Listed by Welcomme (1988) as 'recorded' in Australia

[4] Listed by McKay (1984) as 'recorded' in Australia

[5] Listed in Fishbase (2004) as 'recorded' in Australia.

Table 5. Establishment risk scores for exotic aquarium finfish species introduced to Australia. A. Successfully introduced. B. Unsuccessfully introduced (recorded but not known to be established). The data from which scores A–E are calculated were all obtained from Fishbase (2004) which does not include records from the entire geographic range of many species. If more complete data were available, many species could have higher scores. The total score is the sum of the scores in columns A–E. Establishment Risk Ranks are calculated from conversions presented in Table 3.

A. Successfully introduced aquarium species	A	B	C	D	E	F	G
	Climate match score 0–8	Overseas range score 0–4	Establishment Score 0–3	Introduction success score 0–4	Taxa risk score 0–5	Total score 0–24	Establishment Risk Rank
European carp *Cyprinus carpio*	7	4	3	4	5	23	Extreme
Goldfish *Carassius auratus*	5	4	3	4	5	21	Extreme
White-cloud mountain minnow *Tanichthys albonubes*	1	4	2	4	3	14	High
Mosquitofish *Gambusia holbrooki + affinis*[2]	8	4	3	4	5	24	Extreme
Guppy *Poecilia reticulata*	5	4	3	4	5	21	Extreme
One-spot live bearer *Phalloceros caudimaculatus*	3	3	2	4	5	17	High
Sailfin molly *Poecilia latipinna*	5	2	3	4	5	19	Very high
Platy *Xiphophorus maculatus*	4	2	3	4	5	18	Very high
Green swordtail *Xiphophorus hellerii*	5	1	3	4	5	18	Very high
Red devil/Midas cichlid *Amphilophus citrinellus*	1	2	2	4	3	12	High
Three-spot cichlid *Cichlasoma trimaculatum*	4	2	0	0	4	10	Moderate
Victoria Burton's haplochromine *Haplochromis burtoni*	2	0	1	2	3	8	Low
Niger cichlid *Tilapia mariae*	1	3	2	4	4	14	High
Oscar *Astronotus ocellatus*	3	4	3	4	5	19	Very high
Blue acara *Aequidens pulcher*[3]	1	2	2	2	3	10	Moderate
Convict cichlid *Archocentrus nigrofasciatus*[3]	4	0	2	4	4	14	High
Jewel cichlid *Hemichromis bimaculatus*[3]	5	3	2	4	5	19	Very high
Redbelly tilapia *Tilapia zillii*[3]	4	4	3	3	4	18	Very high
Jack dempsey *Cichlasoma octofasciatum*[4]	4	2	3	4	4	17	High
Weather loach *Misgurnus anguillicaudatus*	2	2	3	4	5	16	High

Table 5 cont.

Three-spot gourami *Trichogaster trichopterus*	5	4	3	4	5	21	Extreme
Chameleon goby *Tridentiger trigonocephalus*[5]	3	1	2	4	5	15	High
Average for successful species (standard deviation)	**3.7 (1.9)**	**2.6 (1.3)**	**2.4 (0.8)**	**3.6 (1.0)**	**4.4 (0.8)**	**16.7 (4.3)**	

[1] Listed by in Kailola (2000) as ‘established’ unless otherwise indicated below.

[2] Although *Gambusia affinis* and *G. holbrooki* are now recognized as separate species, with only *G. holbrooki* known to be established in Australia, *G. holbrooki* was once considered to be a sub-species of *G. affinis* and it is clear that Fishbase records do not accurately separate the two taxa according to their current classification

[3] Listed by Mark Lintermans (in prep.) as ‘established’ in Australia.

[4] Listed by Mark Lintermans (pers. comm. 8 April 2004) as ‘established’ in Australia.

[5] Listed by Howard Gill (pers. comm. 15 April 2004) as ‘established’ in Australia.

Table 5 cont.

B. Unsuccessfully introduced aquarium species (recorded but not known to be established)	A	B	C	D	E	F	G
	Climate match score 0–8	Overseas range score 0–4	Establish-ment score 0–3	Introduction success score 0–4	Taxa risk score 0–5	Total score 0–24	Establishment Risk Rank
Rosy barb *Puntius conchonius*	5	3	3	4	5	20	Very high
Sumatra barb *Puntius tetrazona*	0	0	3	3	5	11	Moderate
Dominican Gambusia *Gambusia dominicensis*[4,5]	1	0	1	2	5	9	Moderate
Green terror *Aequidens rivulatus*	1	1	1	2	3	8	Low
Firemouth cichlid *Thorichtys meeki*	4	0	3	4	4	15	High
Banded cichlid *Heros severus*	2	2	0	0	4	8	Low
Redhead cichlid *Vieja synspila*	0	4	1	2	4	11	Moderate
Pearl cichlid *Geophagus brasiliensis*	2	1	0	0	3	6	Very low
Blue tilapia *Oreochromis aureus*[2]	4	3	3	4	4	18	Very high
Wami tilapia *Oreochromis urolepis hornorum*[3]	4	1	3	4	4	16	High
American flagfish *Jordanella floridae*[4]	1	0	1	2	5	9	Moderate
Average for unsuccessful species (standard deviation)	**2.2 (1.8)**	**1.4 (1.4)**	**1.7 (1.3)**	**2.5 (1.5)**	**4.2 (0.8)**	**11.9 (4.6)**	

[1] Listed by in Kailola (2000) as ‘recorded’ but not known to be established, or only maintained by repeated releases, unless otherwise indicated.

[2] Listed by Lever (1996) as ‘recorded’ in Australia.

[3] Listed by Welcomme (1988) as ‘recorded’ in Australia

[4] Listed by McKay (1984) as ‘recorded’ in Australia

[5] Listed in Fishbase (2004) as ‘recorded’ in Australia.

Acknowledgements

This project was conducted for the Department of the Environment and Heritage and funded by the Natural Heritage Trust.

We thank Simon Knapp and Simon Barry for conducting statistical analyses. We also thank Tricia Kailola, Mark Lintermans, Jeff Johnson and Howard Gill for advice on exotic fish introductions to Australia. Finally we thank Michelle Bausch and Jane Holloway for assistance with finding references, conducting Climate matches and preparing figures, Quentin Hart for editing and Alex McNee for advice on accessing fish data.

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Appendix A

Factors affecting establishment success of exotic fish introduced to Australia

The following five scores (Scores A–E) contribute to establishment risk: higher scores = higher risk.

Score A (Climate match score to Australia 0–8):

Climate matches are calculated using the software CLIMATE with species' distribution ranges (excluding Australian ranges) obtained from Fishbase (2004). CLIMATE output data (Appendix E, Table E1) are converted to a single Climate Match Index (Appendix E, Table E1) for each species using the following formula:

Climate Match Index = 20(number of squares within 10% of the mean ie highest match) + 10(20% of mean) + 5(30% of mean) + 2(20% of mean) + 1(50% of mean).

The Climate Match Index for each species is converted to a Climate Match Score A:

0: ≤ 11

1: 10 – 100

2: 101– 200

3: 201–500

4: 501–1000

5: 1001– 2500

6: 2501–3000

7: 3001–4000

8: ≥4001

Score B (Overseas range score 0–4):

Number of 1^o latitude by 1^o longitude grid squares in which an occurrence of the species is recorded in Fishbase (2004) excluding Australian occurrence records.

The total number of grid squares for each species (Appendix F, Table F1) are converted to an Overseas Range Score B:

0: ≤ 5

1: 5–10

2: 11–20

3: 21–30

4: ≥ 31

Score C (Establishment score 0–3):

Locations where successful introductions of the species have occurred (excluding Australian introductions) – from Fishbase (2004). Where there are no recorded introductions, a moderate risk ranking is given, although a precautionary approach could warrant a higher risk score being given. The data are in Appendix F Table F1

Score C:

0: Introduced but never established

1: Never introduced

2: Only established exotic population(s) on island(s) or on one continent (from choice of five continents not including Australia: 1 Africa; 2 Europe; 3 Asia; 4 North and Central America; or 5 South America)

3: Established exotic populations on more than one continent (excluding Australia).

Score D (Introduction success score 0–4):

The number of known successful introductions of the species worldwide expressed as a proportion of the total number of introductions (excluding Australian introductions) – from Fishbase (2004). Where there are no recorded introductions, a moderate risk ranking is given, although a precautionary approach could warrant a higher risk score being used. The data are in Appendix F Table F1.

Score D:

0: Introduced but success rate = 0

1: Success rate of $>0 \le 0.25$

2: Success rate of $>0.25 \le 0.5$ **OR**
Never introduced

3: Success rate of $>0.5 \le 0.75$

4: Success rate of $>0.75 \le 1.0$

Score E (Taxa risk score 0–5)

Success rates for worldwide introductions of the family or genus of the species being assessed. The data are in Appendix D, Table D1.

Genus risk score: The genus risk score is used as the taxa risk score when number introduction events of all species within the same genus as the species being assessed ≥ 4.

Genus risk score based on proportion of successful introductions (number of successful introductions/total number of introductions) recorded worldwide for all species within the same genus as the species being assessed.

Score E:
0 = Very low: Success rate = 0%
1 = Low: Success rate >0%<10
2 = Moderate: Success rate 10%–25%
3 = High: Success rate >25%<40%
4 = Very high: Success rate 40%–60%
5 = Extreme: Success rate >60%

Family risk score: The family risk score is used as the taxa risk score when number of introduction events of all species within the same genus as the species being assessed = 0–3, to increase the sample size.

Family risk score based on proportion of successful introductions (number of successful introductions/total number of introductions) recorded worldwide for all species within the same family as the species being assessed. (Where there are no recorded introductions, or where sample sizes are small, a moderate (or more moderate) risk ranking is given, although a precautionary approach could warrant a higher risk scores being given.)

Score E:

0 = Very low: Success rate = 0% (number introductions ≥ 3)

1 = Low: Success rate = 0% (number introductions 1–2)

2 = Moderate: Success rate = 1–25% (any number introductions)

- *OR*
Never introduced (number introductions 0)
3 = High: Success rate >25%–60% (any number introductions)
4 = Very high: Success rate >60% (number introductions 1–2)
5 = Extreme: Success rate >60% (number introductions ≥ 3)

Table A1. Establishment risk scores for exotic finfish species introduced to Australia: (A) successfully introduced, (B) unsuccessfully introduced (recorded but not known to be established). The input values for CLIMATE (Appendix E, Figure E1), overseas range (Appendix F, Table F1), establishment (this table) and introduction success (Appendix F, Table F1) were all obtained from Fishbase (2004), which does not include records from the entire geographic range of many species. If more complete data were available, many species could have higher scores for climate match and overseas range and some species would also probably obtain higher scores on the other risk factors too. The taxa risk scores (Appendix D, Table D1) were derived from data on worldwide species introductions collated by Arthington et al. (1999).

A: Successfully introduced species[1]	**Family**	Climate match score 0–8	Overseas range score 0–4	Establish-ment score 0–3	Introduction success score 0–4	Taxa risk score 0–5
European carp *Cyprinus carpio*	Cyprinidae	7	4	3	4	5
Tench *Tinca tinca*		6	3	3	4	5
Goldfish *Carassius auratus*		5	4	3	4	5
Roach *Rutilus rutilus*		4	4	3	4	3
White-cloud mountain minnow *Tanichthys albonubes*[2]		1	4	2	4	3
Mosquitofish *Gambusia holbrooki + affinis*[2]	Poeciliidae	8	4	3	4	5
Guppy *Poecilia reticulata*		5	4	3	4	5
One-spot live bearer *Phalloceros caudimaculatus*		3	3	2	4	5
Sailfin molly *Poecilia latipinna*		5	2	3	4	5
Platy *Xiphophorus maculatus*		4	2	3	4	5
Green swordtail *Xiphophorus hellerii*		5	1	3	4	5
Mozambique tilapia *Oreochromis mossambicus*	Cichlidae	8	4	3	4	4
Red devil/Midas cichlid *Amphilophus citrinellus*		1	2	2	4	3
Three-spot cichlid *Cichlasoma trimaculatum*		4	2	0	0	4
Victoria Burton's haplochromine *Haplochromis burtoni*		2	0	1	2	3
Niger cichlid *Tilapia mariae*		1	3	2	4	4
Oscar *Astronotus ocellatus*		3	4	3	4	5
Blue acara *Aequidens pulcher*[3]		1	2	2	2	3
Convict cichlid *Archocentrus nigrofasciatus*[3]		4	0	2	4	4

A: Successfully introduced species[1]	**Family**	Climate match score 0–8	Overseas range score 0–4	Establish-ment score 0–3	Introduction success score 0–4	Taxa risk score 0–5
Jewel cichlid *Hemichromis bimaculatus*[3]		5	3	2	4	5
Redbelly tilapia *Tilapia zillii*[3]		4	4	3	3	4
Jack Dempsey *Cichlasoma octofasciatum* [5]		4	2	3	4	4
Weather loach *Misgurnus anguillicaudatus*	Cobitidae	2	2	3	4	5
Redfin perch *Perca fluviatilis*	Percidae	4	3	3	4	5
Rainbow trout *Oncorhynchus mykiss*	Salmonidae	8	4	3	4	3
Brown trout *Salmo trutta*		5	4	3	4	4
Brook trout *Salvelinus fontinalis*		1	4	3	3	4
Three-spot gourami *Trichogaster trichopterus*	Osphronemidae	5	4	3	4	5
Yellowfin goby *Acanthogobius flavimanus*[3,4]	Gobiidae	1	1	2	4	5
Goby *Acentrogobius pflaumii*[3,4]		1	0	1	2	5
Chameleon goby *Tridentiger trigonocephalus*[4, 6]		3	1	2	4	5
Mean successful (standard deviation)		**3.9 (2.2)**	**2.7 (1.4)**	**2.5 (0.77)**	**3.6 (0.92)**	**4.4(0.8)**

[1] Listed by in Kailola (2000) as ‘established’ unless otherwise indicated below.

[2] Although *Gambusia affinis* and *G. holbrooki* are now recognized as separate species, with only *G. holbrooki* known to be established in Australia, *G. holbrooki* was once considered to be a sub-species of *G. affinis* and it is clear that Fishbase records do not accurately separate the two taxa according to their current classification.

[3] Listed by Mark Lintermans (2004 in prep.) as ‘established’ in Australia.

[4] Gobies that probably entered Australia via ballast water (Mark Lintermans pers. comm. 19 April 2004).

[5] Listed by Mark Lintermans (pers. comm. 8 April 2004) as ‘established’ in Australia.

[6] Listed by Howard Gill (pers. comm. 15 April 2004) as ‘established’ in Australia.

Table A1 cont.

B: Unsuccessfully introduced species[1] (recorded but not known to be established)	**Family**	Climate match score 0–8	Overseas range score 0–4	Establish-ment score 0–3	Introduction success score 0–4	Taxa risk score 0–5
Rosy barb *Puntius conchonius*	Cyprinidae	5	3	3	4	5
Sumatra barb *Puntius tetrazona*		0	0	3	3	5
Dominican gambusia *Gambusia dominicensis*[4,5]	Poeciliidae	1	0	1	2	5
Green terror *Aequidens rivulatus*	Cichlidae	1	1	1	2	3
Firemouth cichlid *Thorichtys meeki*		4	0	3	4	4
Banded cichlid *Heros severus*		2	2	0	0	4
Redhead cichlid *Vieja synspila*		0	4	1	2	4
Pearl cichlid *Geophagus brasiliensis*		2	1	0	0	3
Blue tilapia *Oreochromis aureus*[2]		4	3	3	4	4
Wami tilapia *Oreochromis urolepis*[3]		4	1	3	4	4
Chinook salmon *Oncorhynchus tshawytscha*	Salmonidae	1	4	2	1	3
Atlantic salmon *Salmo salar*		5	4	3	1	4
Plainfin frogfish *Porichthys notatus*	Batrachoididae	2	4	1	2	2
Japanese seabass *Lateolabrax japonicus*	Percichthyidae	2	2	1	2	0
Sobaity seabream *Sparidentex hasta*	Sparidae	0	0	1	2	2
Common triplefin *Forsterygion lapillum*	Tripterygiidae	3	0	1	2	2
Redbanded perch *Hypoplectrodes huntii*	Serranidae	3	0	1	2	2
American flagfish *Jordanella floridae*[4]	Cyprinodontidae	1	0	1	2	5
Mean unsuccessful (standard deviation)		**2.2 (1.7)**	**1.6 (1.6)**	**1.6 (1.1)**	**2.2 (1.2)**	**3.4 (1.4)**

[1] Listed by in Kailola (2000) as ‘recorded’ but not known to be established, or only maintained by repeated artificial releases, unless otherwise indicated below.

[2] Listed by Lever (1996) as ‘recorded’ in Australia.

Table A1 cont.

[3] Listed by Welcomme (1988) as ‘recorded’ in Australia

[4] Listed by McKay (1984) as ‘recorded’ in Australia

[5] Listed in Fishbase (2004) as ‘recorded’ in Australia.

Appendix B

Statistical analysis of factors affecting establishment success of exotic fish introduced to Australia

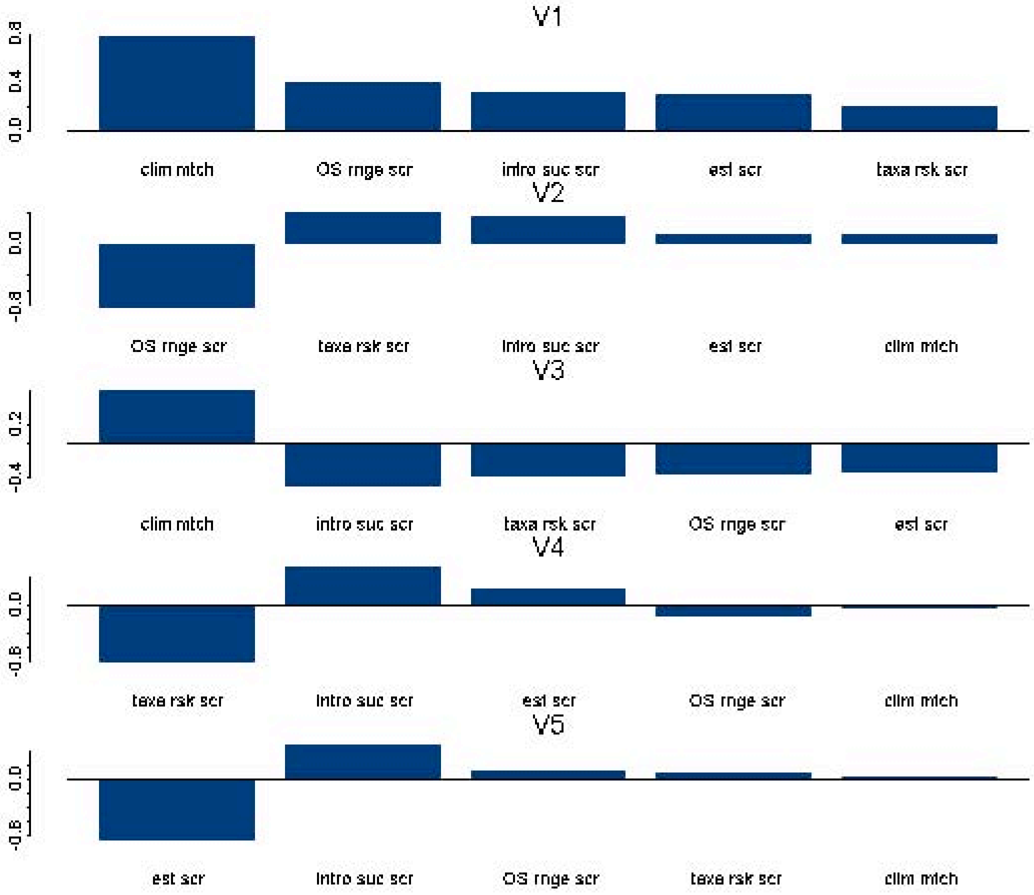
Simon Knapp, Bureau of Rural Sciences

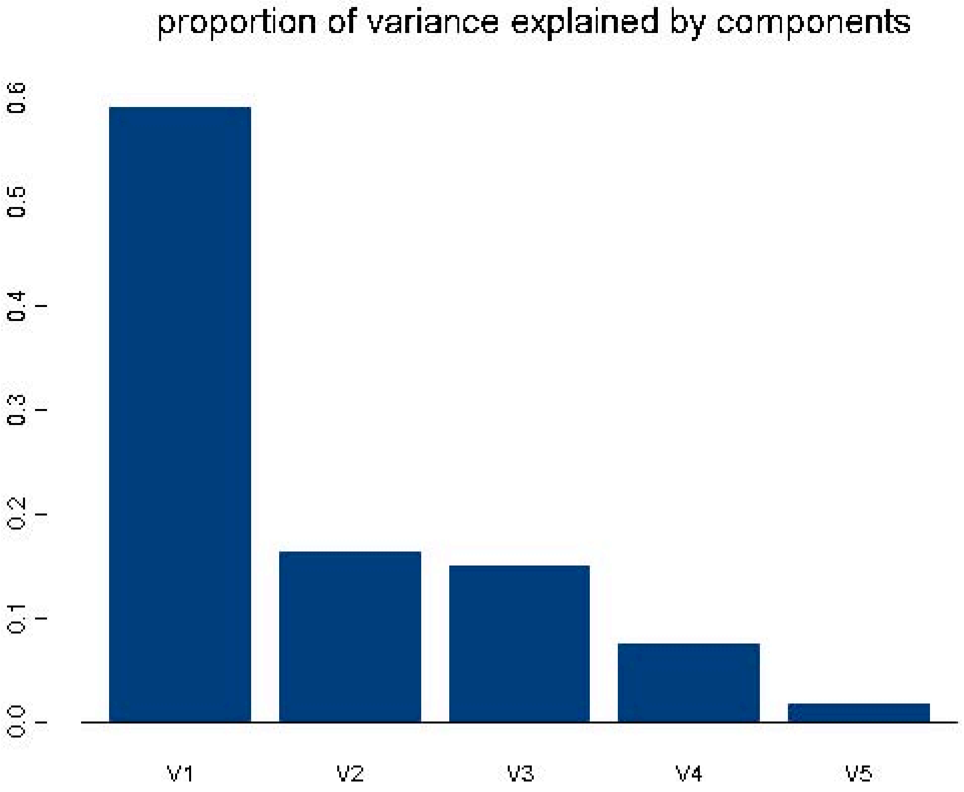
Three analyses were performed on the data presented in Appendix A Table A1:

1. logistic regression using principle components
2. categorical and regression tree analysis (CART)
3. stepwise regression.

1. Principle components logistic regression

First thing I did was a principle components analysis. The results of the analysis are shown in the following plot, and what it says is that as follows: if we use the weights shown in the first plot to create new variables from the raw variables (where the new variables are given by the titles of the bar charts, then the new variables explain the proportion of the variance shown in the second plot variables (names ‘V1’ etc.).


V1
0.0
0.4
0.8
clim mtch
OS rnge scr
intro suc scr
est scr
taxa rsk scr
V2
-0.8
0.0
OS rnge scr
taxa rsk scr
intro suc scr
est scr
clim mtch
V3
-0.4
0.2
clim mtch
intro suc scr
taxa rsk scr
OS rnge scr
est scr
V4
-0.8
0.0
taxa rsk scr
intro suc scr
est scr
OS rnge scr
clim mtch
V5
-0.8
0.0
est scr
intro suc scr
OS rnge scr
taxa rsk scr
clim mtch



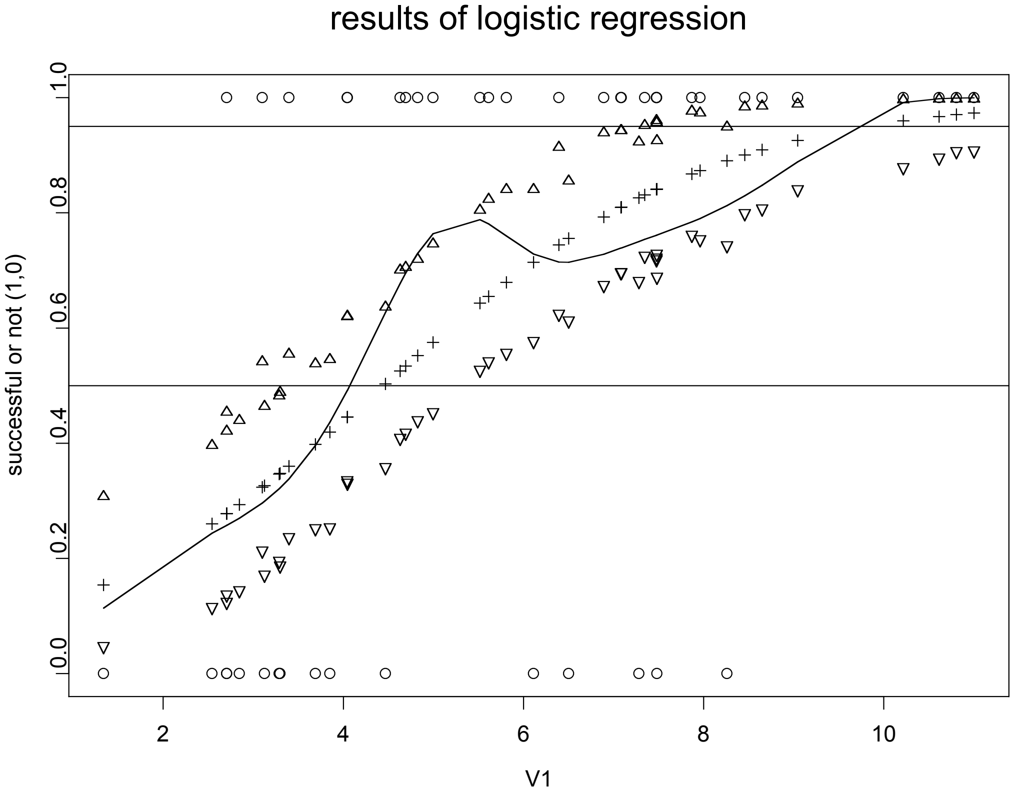
We can now use these variables as predictors in a logistic regression, and we will probably find that only the first is needed:

Running a logistic model with the first two components gives the following sequential analysis of variance, which tells us that V1 is significant even after inclusion of V2, and that V2 is not significant (loosely - this table sequentially includes variables in the model and looks at the change in the residual 'errors').

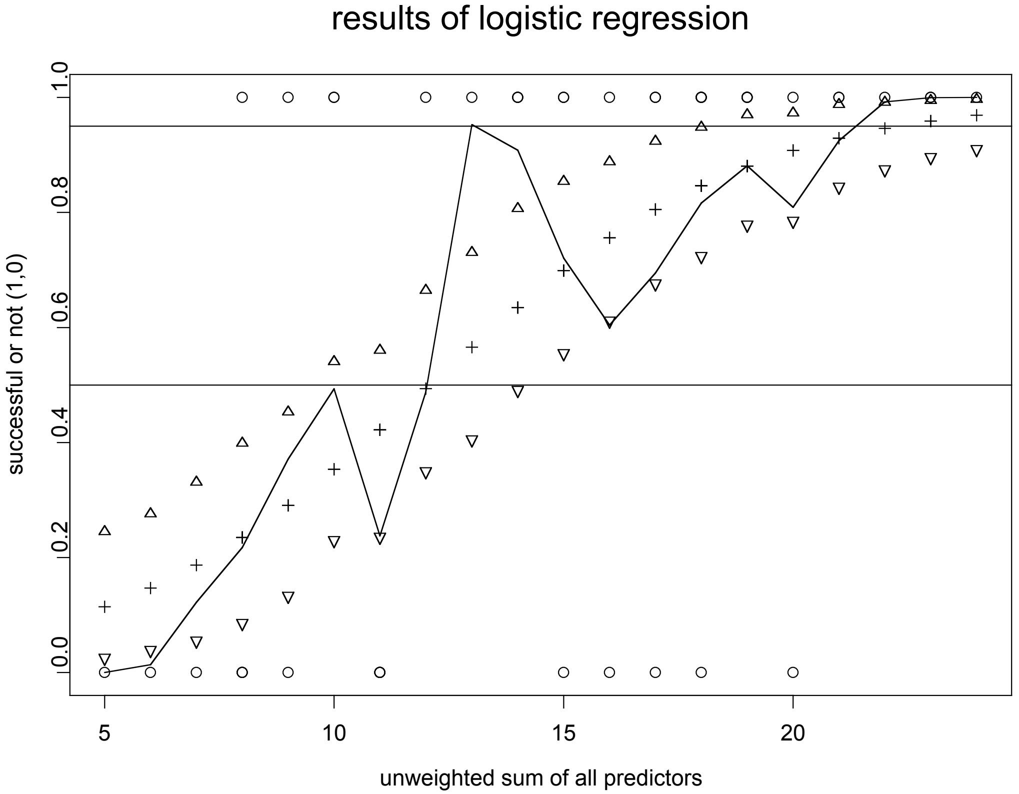
Vars	Df	Deviance	Resid. Df	Resid. Dev	Pr(Chi)
NULL			48	64.4377993	NA
V2	1	0.59119	47	63.8466091	0.441959
V1	1	14.32784	46	49.5187677	0.000154

The next plot shows graphical representations of the results.

- The circles show data from Appendix A.
- The crosses are the fitted values from the regression.
- The black line is the result of running a kernel smoother over the data.
- The triangles show the upper and lower bootstrap confidence bounds for 100 replicates (note that the principle components are only calculated once for simplicity and hence the confidence bounds are narrower than they should be – one should really calculate the principle components for each replicate, but then the bounds are much harder to calculate).
- The horizontal lines are at 0.5 and 0.95.

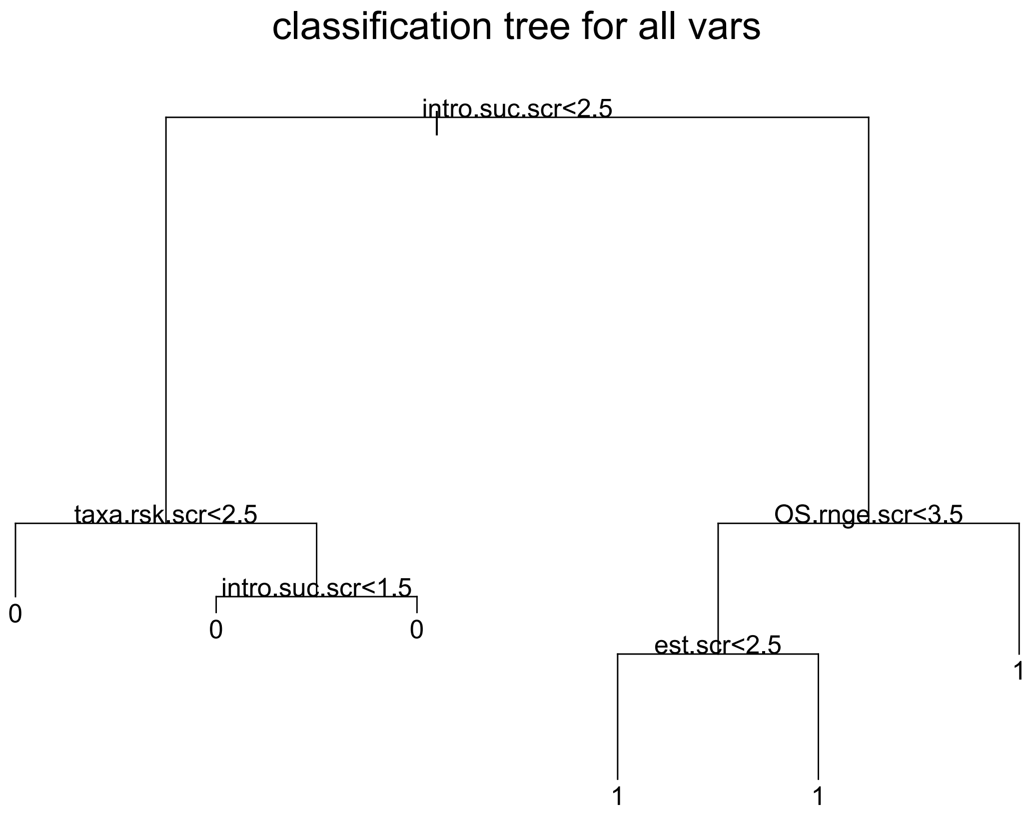


The next plot shows the same thing for the unweighted sum of the predictors (Column F of Table 5 (note that I simply used the same smoothing parameter in the kernel smoother as in the plot above), the definition of the symbols is the same.

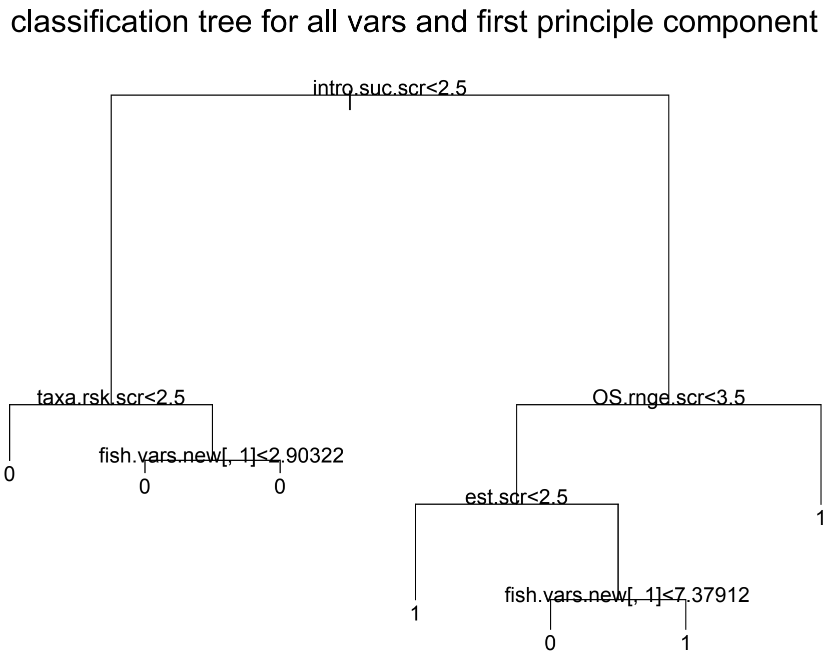


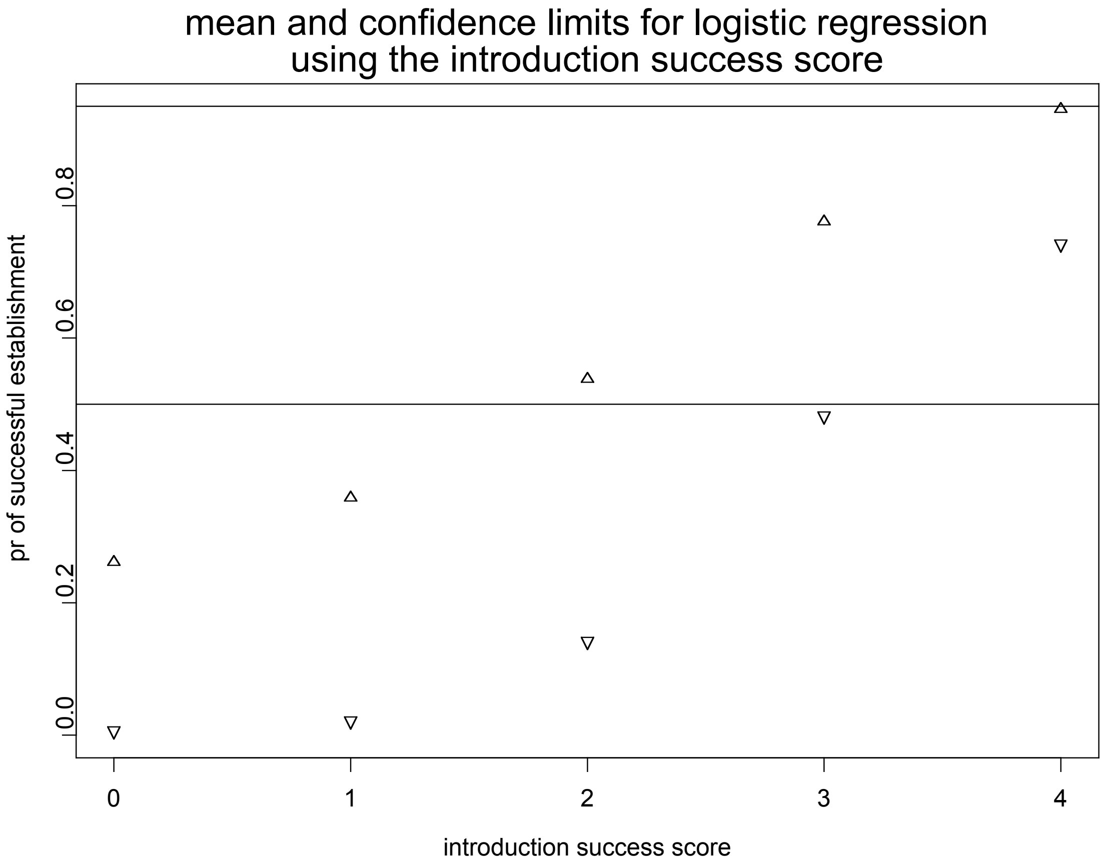
2. CART analysis

A classification tree produced by S-plus, suggests that the introduction success score is the only thing you need as a predictor. It also suggests that the relationships differ depending on whether this score is high or low (though these variables add nothing!).



One thing that is interesting is when we include the first principle component from the previous analysis, which gives the following tree, suggesting that it is not as useful for categorisation as some of the raw variables. Visually scanning down the introduction success score column in the data does reveal a lot of fours and fives where there are ones in the response. It inspired me to try the logistic regression on the introduction success score, which gave the second plot, where only the confidence limits are shown. This plot shows less predictive ability than the above regressions.


classification tree for all vars and first principle component



To assess the accuracy of the CART using all the variables, I did a cross validation, and it predicted with 77.6% accuracy. The one using the principle components predicted with 63.3% accuracy.

3. Stepwise Regression

The final analysis was a (backward) stepwise regression. Blindly using the S-plus procedure gives us the following output:

start of output
```
Start:  AIC= 52.7032
 fish$resp ~ clim.mtch + OS.rnge.scr + est.scr + intro.suc.scr + taxa.rsk.scr

Single term deletions

Model:
fish$resp ~ clim.mtch + OS.rnge.scr + est.scr + intro.suc.scr + taxa.rsk.scr

scale:  1

              Df Sum of Sq      RSS       Cp
       <none>              44.69234 56.69234
    clim.mtch  1  0.866529 45.55887 55.55887
  OS.rnge.scr  1  3.234265 47.92661 57.92661
      est.scr  1  2.350385 47.04273 57.04273
intro.suc.scr  1  5.809438 50.50178 60.50178
 taxa.rsk.scr  1  2.752168 47.44451 57.44451
```

```
Step:  AIC= 51.6125
 fish$resp ~ OS.rnge.scr + est.scr + intro.suc.scr + taxa.rsk.scr

Single term deletions

Model:
fish$resp ~ OS.rnge.scr + est.scr + intro.suc.scr + taxa.rsk.scr

scale:  1

              Df Sum of Sq      RSS       Cp
       <none>              43.83506 53.83506
  OS.rnge.scr  1  3.905155 47.74022 55.74022
      est.scr  1  1.803110 45.63817 53.63817
intro.suc.scr  1  5.700752 49.53582 57.53582
 taxa.rsk.scr  1  2.745322 46.58039 54.58039

Step:  AIC= 51.6901
 fish$resp ~ OS.rnge.scr + intro.suc.scr + taxa.rsk.scr
```

```
Call:
glm(formula = fish$resp ~ OS.rnge.scr + est.scr + intro.suc.scr + taxa.rsk.scr, family =
   binomial(link = logit), data = fish)

Coefficients:
 (Intercept) OS.rnge.scr   est.scr intro.suc.scr taxa.rsk.scr
   -5.295505   0.5597435 -1.009056      1.351018    0.7003182

Degrees of Freedom: 49 Total; 44 Residual
Residual Deviance: 41.61253
#### end of output ####
```

This suggests that the best model includes Overseas range score, Establishment score, Introduction success score, and the Taxa risk score (it is interesting to note that the coefficient – on the linear scale – of Establishment score is negative… bear in mind the colinearity while considering this). The procedure gives the same result if both forward and backward selection is allowed, and includes all five variables if only forward is used. This procedure is using the AIC as the criteria for dropping inserting variables. When this process is conducted manually using F t-tests, it only leaves Introduction success score in the model, which agrees with the CART above.

Appendix C

Environmental tolerances and maximum body sizes of finfish introduced to Australia

Table C1. Environmental tolerances for acidity (pH), water hardness (dH) and salinity and maximum body sizes for exotic finfish species introduced to Australia: (A) successfully introduced, (B) unsuccessfully introduced (recorded but not known to be established). Dashes indicate data unavailable. (Data collated from Fishbase 2004)

A: Successfully introduced species	pH range	pH difference	dH range	dH difference	Salt tolerance*	Maximum size (cm)
European carp *Cyprinus carpio*	7.0-7.5	0.5	10.0-15.0	5.0	f,b	120
Tench *Tinca tinca*	-	-	-	-	f,b	84
Goldfish *Carassius auratus*	6.0-8.0	2.0	5.0-19.0	14	F	59
Roach *Rutilus rutilus*	7.0-7.5	0.5	10.0-15.0	5.0	f,b	46
White-cloud mountain minnow *Tanichthys albonubes*	6.0-8.0	2.0	5.0-19.0	14	F	4
Mosquitofish *Gambusia holbrooki + affinis*	6.0-8.8	2.8	5.0-19.0	14	f,b,m	8
Guppy *Poecilia reticulata*	7.0-8.0	1.0	9.0-19.0	10	f,b	5
One-spot live bearer *Phalloceros caudimaculatus*	7.0-8.0	1.0	9.0-19.0	10	f,b	3.5
Sailfin molly *Poecilia latipinna*	-	-	-	-	f,b	15
Platy *Xiphophorus maculatus*	7.0-8.0	1.0	9.0-19.0	10	F	6
Green swordtail *Xiphophorus hellerii*	7.0-8.0	1.0	9.0-19.0	10	f,b	16
Mozambique tilapia *Oreochromis mossambicus*	-	-	-	-	f,b	39
Red devil/Midas cichlid *Amphilophus citrinellus*	-	-	-	-	F	24.4
Three-spot cichlid *Cichlasoma trimaculatum*	-	-	-	-	f	36.5
Victoria Burton's haplochromine *Haplochromis burtoni*	8.5-9.0	0.5	12.0-16.0	4	f	15
Niger cichlid *Tilapia mariae*	6.0-8.0	2.0	5.0-19.0	14	f,b	39.4
Oscar *Astronotus ocellatus*	6.0-8.0	2.0	5.0-19.0	14	f	45.7

Table C1 cont.

Blue acara *Aequidens pulcher*	6.5-8.0	1.5	25.0?	?	f	16
Convict cichlid *Archocentrus nigrofasciatus*	7.0-8.0	1.0	9.0-20.0	11	f	10
Jewel cichlid *Hemichromis bimaculatus*	6.5-7.5	1.0	4.0-16.0	12	f,b	13.6
Redbelly tilapia *Tilapia zillii*	6.0-9.0	3.0	5.0-20.0	15	f,b	40
Jack Dempsey *Cichlasoma octofasciatum*	7.0-8.0	1.0	9.0-20.0	11	f	25
Weather loach *Misgurnus anguillicaudatus*	-	-	-	-	f	24.8
Redfin perch *Perca fluviatilis*	7.0-7.5	0.5	8.0-12.0	4.0	f,b	51
Rainbow trout *Oncorhynchus mykiss*	-	-	-	-	f,b,m	120
Brown trout *Salmo trutta*	-	-	-	-	f,b,m	140
Brook trout *Salvelinus fontinalis*	-	-	-	-	f,b,m	86
Three-spot gourami *Trichogaster trichopterus*	6.0-8.0	2.0	5.0-19.0	14	f	15
Yellowfin goby *Acanthogobius flavimanus*	-	-	-	-	f,b,m	30
Goby *Acentrogobius pflaumii*	-	-	-	-	b,m	
Chameleon goby *Tridentiger trigonocephalus*	-	-	-	-	f,b,m	11
Average for successful fish (standard deviation)		**1.4 (0.8)**		**10.6 (3.8)**		**38 (37)**

Table C1 cont.

B: Unsuccessfully introduced species						
Rosy barb *Puntius conchonius*	6.0-8.0	2.0	5.0-19.0	14.0	f	14
Sumatra barb *Puntius tetrazona*	6.0-8.0	2.0	5.0-19.0	14.0	f	7
Dominican gambusia *Gambusia dominicensis*	-	-	-	-	f,b	2.5
Green terror *Aequidens rivulatus*	6.5-8.0	1.5	25.0	?	f	20
Firemouth cichlid *Thorichtys meeki*	6.5-7.5	1.0	10.0	?	f	17
Banded cichlid *Heros severus*	5.0-6.5	1.5	0.0-6.0	6.0	f,b	20
Redhead cichlid *Vieja synspila*	7.0-8.0	1.0	9.0-20.0	11.0	f,b	35
Pearl cichlid *Geophagus brasiliensis*	6.5-7.0	0.5	5.0-10.0	5.0	f,b	28
Blue tilapia *Oreochromis aureus*	-	-	-	-	f,b	45.7
Wami tilapia *Oreochromis urolepis*	-	-	-	-	f,b	24
Chinook salmon *Oncorhynchus tshawytscha*	-	-	-	-	f,b,m	150
Atlantic salmon *Salmo salar*	-	-	-	-	f,b,m	150
Plainfin frogfish *Porichthys notatus*	-	-	-	-	m	38
Japanese seabass *Lateolabrax japonicus*	-	-	-	-	f,b,m	102
Sobaity seabream *Sparidentex hasta*	-	-	-	-	m	50
Common triplefin *Forsterygion lapillum*	-	-	-	-	m	6.7
Redbanded perch *Hypoplectrodes huntii*	-	-	-	-	m	20
American flagfish *Jordanella floridae*	-	-	-	-	f,b	6
Average for unsuccessful fish (standard deviation)		**1.4 (0.6)**		**10.0 (4.3)**		**41 (46)**

*f = occurs in freshwater; b = occurs in brackish water; m = occurs in water with salinity ≥ seawater.

Appendix D

World finfish introductions: establishment success rates

Table D1. Total number of introductions and number of successful introductions of exotic finfish worldwide, for 352 species[1] in 172 genera and 53 families (Data collated from Arthington et al. 1999). Logistic regression analysis indicates that both family and genus are highly significantly (P<0.0001) correlated with introduction success. The risk scores for introduction success for each family and genus are calculated using the formulas presented in the text below.

Family name	Family risk score	Genus name	Genus risk score[2]	Species number[1]	Number of introduction events	Number of successful introductions
Acipenseridae	2	*Acipenser*	1	1	7	1
				2	1	0
				3	6	0
				4	1	0
				5	7	0
				6	1	0
				7	1	0
		Huso	0	8	2	0
				9	1	0
				10	1	0
Adrianichthyidae	4	*Oryzias*	0	11	6	0
Anabantidae	3	*Anabas*	5	12	4	3
		Ctenopoma	-	13	1	1
				14	1	0
		Helostoma	-	15	1	0
Anguillidae	3	*Anguilla*	4	16	10	6
				17	3	2
				18	7	1
				19	1	0
Anostomidae	1	*Leporinus*	-	20	1	0
Apocheilidae	3	*Aplocheilus*	-	21	1	0
				22	1	1
		Nothobranchius	-	23	2	0
		Rivulus	-	24	1	1
Atherinidae	5	*Odontesthes*	5	25	8	6
Belonidae	1	*Strongylura*	-	26	1	0
		Xenentodon	-	27	1	0
Belontiidae	5	*Betta*	5	28	2	2
				29	6	4
				30	2	2
				31	1	1
				32	1	0

Table D1 cont.

		Trichogaster	5	33	2	2
				34	4	2
				35	4	3
				36	1	1
				37	13	8
				38	1	0
				39	9	5
				40	1	1
Callichthyidae	1	*Corydoras*	-	41	1	0
				42	1	0
Catostomidae	3	*Carpoides*	-	43	3	3
		Catostomus	-	44	1	0
		Ictiobus	4	45	4	2
				46	9	3
				47	8	4
Centrarchidae	5	*Ambloplites*	-	48	3	3
		Lepomis	5	49	5	4
				50	13	8
				51	25	21
				52	2	2
				53	21	15
				54	4	2
				55	1	0
		Micropterus	4	56	1	1
				57	20	6
				58	4	2
				59	64	43
		Pomoxis	5	60	3	2
				61	5	3
Centropomidae	3	*Lates*	4	62	3	0
				63	1	0
				64	6	4
Channidae	5	*Channa*	5	65	1	1
				66	3	1
				67	1	1
				68	10	7
Characidae	2	*Astyanax*	-	69	1	1
		Colossoma	1	70	15	1
				71	1	0
		Gymnocorymbus	-	72	2	2
		Hyphessobrycon	-	73	1	0
		Paracheirodon	-	74	1	0
		Piaractus	0	75	10	0
		Serrasalmus	-	76	1	0
		Thayeria	-	77	1	0
Cichlidae	3	*Aequidens*	-	78	2	0
				79	1	0

Table D1 cont.

		Amphilophus	-	80	2	2
		Astatoreochromis	5	81	5	3
		Astronotus	5	82	11	7
		Aulonocara	-	83	1	0
		Boulengerochromis	-	84	1	0
		Cichla	5	85	8	6
				86	1	1
		Cichlasoma	4	87	1	0
				88	1	1
				89	3	3
				90	1	0
				91	4	3
				92	1	0
				93	6	2
				94	3	3
				95	2	0
				96	2	0
				97	1	0
				98	1	0
				99	1	0
				100	2	1
				101	1	1
		Etroplus	2	102	4	1
		Geophagus	-	103	2	0
				104	1	1
		Haplochromis	-	105	1	0
		Hemichromis	5	106	4	4
				107	1	0
		Labeotropheus	-	108	1	0
		Melanochromis	-	109	1	0
		Oreochromis	4	110	2	1
				111	42	23
				112	2	2
				113	1	1
				114	4	2
				115	21	5
				116	2	1
				117	91	66
				118	1	0
				119	79	40
				120	1	0
				121	1	0
				122	10	3
				123	6	2
				124	1	0
				125	21	17
				126	2	0

Table D1 cont.

		Parachromis	5	127	6	5
		Pelvicachromis	-	128	2	0
		Pseudotropheus	-	129	1	0
				130	1	0
		Pterophyllum	0	131	3	0
				132	1	0
		Sarotherodon	3	133	8	2
				134	4	2
		Serranochromis	5	135	2	1
				136	2	2
		Symphysodon	-	137	1	0
		Tilapia	4	138	1	0
				139	3	2
				140	32	18
				141	3	2
				142	1	0
				143	31	16
Citharinidae	4	*Distichodus*	-	144	1	1
Clariidae	3	*Clarias*	3	145	9	6
				146	2	1
				147	31	9
				148	5	2
Clupeidae	5	*Alosa*	-	149	1	1
		Dorosoma	-	150	2	2
		Limnothrissa	5	151	6	5
		Potamalosa	-	152	1	0
Cobitidae	5	*Misgurnus*	5	153	6	5
				154	2	2
Curimatidae	1	*Prochilodus*	-	155	1	0
Cyprinidae	3	*Abramus*	4	156	1	1
				157	2	2
				158	5	1
		Acrossocheilus	-	159	1	0
		Alburnus	-	160	2	2
		Aristichthys	2	161	71	15
		Barbodes	5	162	18	13
				163	2	0
		Barbus	4	164	2	1
				165	1	1
				166	1	1
				167	1	0
				168	4	1
				169	1	1
				170	1	1
				171	1	0
				172	1	0
				173	2	1

Table D1 cont.

		Capoeta	-	174	1	0
		Carassius	5	175	52	43
				176	2	1
				177	14	7
		Catla	3	178	14	4
		Chondrostoma	-	179	2	1
		Ctenopharyngodon	1	180	91	8
		Cyprinus	5	181	122	86
				182	2	0
		Danio	-	183	1	1
				184	2	0
		Gila	-	185	1	0
				186	1	0
		Gobio	5	187	4	4
		Hemibarbus	-	188	1	1
		Hemiculter	5	189	4	4
		Hypophthalmichthys	2	190	80	18
				191	1	0
		Labeo	2	192	1	1
				193	19	1
		Leucaspius	-	194	3	3
		Leuciscus	3	195	9	2
				196	1	1
				197	1	0
		Megalobrama	3	198	3	2
				199	4	0
		Mesobola	-	200	1	1
		Mylopharyngodon	2	201	20	4
		Notemigonus	-	202	1	0
		Opsariichthys	-	203	1	1
				204	1	1
		Pachychilon	-	205	2	2
		Parabramis	0	206	4	0
		Phoxinus	-	207	2	1
		Pimephales	4	208	5	3
		Pseudorasbora	5	209	19	17
		Puntius	5	210	2	2
				211	9	6
				212	2	1
				213	2	2
				214	1	0
				315	1	1
				216	3	2
				217	1	0
				218	6	4
				219	1	0
				220	7	3

Table D1 cont.

				221	4	3
		Rasbora	-	222	1	0
				223	1	1
		Rhodeus	5	224	2	2
				225	5	3
		Rutilus	3	226	2	0
				227	1	1
				228	8	3
		Scardinius	5	229	7	6
		Schizothorax	-	230	1	0
		Tanichthys	-	231	1	1
		Tinca	5	232	21	15
		Tor	-	233	3	0
		Varicorhinus	-	234	1	0
		Vimba	-	235	3	1
Cyprinodontidae	5	*Aphanius*	-	236	3	2
Eleotridae	4	*Hypseleotris*	-	237	1	1
Ethrinidae	1	*Hoplias*	-	238	2	0
Esocidae	3	*Esox*	4	239	13	8
				240	1	0
				241	2	1
Fundulidae	3	*Fundulus*	4	242	1	0
				243	4	2
				244	1	1
Gasterosteidae	5	*Culaea*	-	245	1	1
		Gasterosteus	5	246	4	3
		Pungitius	-	247	1	0
Gobiidae	5	*Acanthogobius*	-	248	2	2
		Neogobius	5	249	1	1
				250	5	4
		Proterorhinus	-	251	3	2
		Rhinogobius	-	252	2	2
		Tridentiger	-	253	3	3
Helostomatidae	3	*Helostoma*	3	254	7	2
Ictaluridae	5	*Ameiurus*	5	255	3	2
				256	22	18
				257	2	2
				258	43	37
		Ictalurus	3	259	32	9
				260	1	0
		Noturus	-	261	2	2
Kuhliidae	1	*Kuhlia*	-	262	1	0
Loricariidae	5	*Ancistrus*	-	263	1	0
		Hypostomus	-	264	1	1
		Pterygoplichthys	-	265	3	3
Moronidae	3	*Dicentrarchus*	-	266	2	0
				267	1	1

Table D1 cont.

		Morone	3	268	1	1
				269	3	1
				270	6	2
				271	1	0
Osmeridae	4	*Hypomesus*	-	272	1	1
		Osmerus	-	273	2	2
Osphronemidae	3	*Osphronemus*	3	274	19	7
Osteoglossidae	5	*Arapaima*	-	275	2	0
		Heterotis	5	276	6	6
Pangasiidae	0	*Pangasius*	0	277	5	0
Percichthyidae	1	*Macquaria*	0	278	1	0
				279	2	0
				280	1	0
Percidae	5	*Gymnocephalus*	-	281	3	2
		Perca	5	282	1	1
				283	8	5
		Sander	5	284	20	14
		Stizostedion	-	285	1	0
Petromyzonidae	1	*Caspiomyzon*	-	286	1	0
Pimelodidae	1	*Rhamdia*	-	287	1	0
Plecoglossidae	3	*Plecoglossus*	-	288	2	1
Pleuronectidae	3	*Platichthys*	-	289	2	1
Poeciliidae	5	*Belonesox*	-	290	1	1
		Cnesterodon	-	291	1	0
		Gambusia	5	292	8	8
				293	48	42
				294	11	11
				295	1	1
		Phalloceros	-	296	3	3
		Poecilia	5	297	10	9
				298	5	5
				299	41	32
				300	4	2
				301	2	1
				302	1	1
		Poeciliopsis	-	303	2	2
		Xiphophorus	5	304	19	14
				305	1	0
				306	10	9
				307	4	3
Polydontidae	0	*Polyodon*	0	308	4	0
Retropinnidae	1	*Retropinna*	-	309	1	0
Salmonidae	3	*Coregonus*	3	310	4	1
				311	1	0
				312	1	0
				313	10	2
				314	13	6

Table D1 cont.

				315	1	0
				316	2	1
				317	1	1
				318	15	7
		Hucho	1	319	12	1
		Oncorhynchus	3	320	1	1
				321	4	1
				322	10	2
				323	4	0
				324	15	2
				325	2	0
				326	99	44
				327	8	2
				328	3	0
				329	17	4
		Salmo	4	330	2	1
				331	20	5
				332	6	2
				333	1	0
				334	1	0
				335	1	1
				336	39	25
		Salvelinus	4	337	12	4
				338	49	29
				339	1	0
				340	19	7
		Stenodus	-	341	1	0
		Thymallus	2	342	2	0
				343	4	1
Schilibidae	1	*Schilbe*	-	344	2	0
Sciaenidae	5	*Aplodinotus*	-	345	1	0
		Bairdiella	-	346	1	1
		Cynoscion	-	347	1	1
Siluridae	3	*Silurus*	4	348	15	9
Synbranchidae	4	*Monopterus*	-	349	1	1
Umbridae	5	*Dallia*	-	350	1	0
		Umbra	5	351	3	1
				352	5	5

[1] Some subspecies are treated as equivalent to species, after Arthington et al. (1999).

[2] No genus risk score is calculated if the total number introduction events for all species within the genus < 4.

The **family risk score** is an index of the introduction success rate for a family. This introduction success rate is calculated as the proportion of successful introductions divided by the total number of introduction events recorded for all species within the family expressed as a percentage:

0 = Very low: Success rate = 0% (number introductions ≥ 3)

1 = Low: Success rate = 0% (number introductions 1–2)

2 = Moderate: Success rate = 1–25% (any number introductions)
OR
Never introduced (number introductions 0)
3 = High: Success rate >25%–60% (any number introductions)
4 = Very high: Success rate >60% (number introductions 1–2
5 = Extreme: Success rate >60% (number introductions ≥ 3)

For example, the family Acipenseridae has one successful introduction out of a total of 28 introduction events = 3.6% giving a family risk score of 2 = moderate.

The **genus risk score** is an index of the introduction success rate for the genus. This introduction success rate is calculated as the number of successful introductions divided by the total number of introduction events recorded for all species within the genus expressed as a percentage. A genus risk score is is only calculated when the total number introduction events for all species within the genus ≥ 4:

0 = Very low: Success rate = 0%
1 = Low: Success rate >0%<10
2 = Moderate: Success rate 10%–25%
3 = High: Success rate >25%<40%
4 = Very high: Success rate 40%–60%
5 = Extreme: Success rate >60%

For example, the genus *Acipenser* has one successful introduction out of a total of 24 introduction events = 4.2% giving a family risk score of 1 = low.

Appendix E

Climate matches for finfish introduced to Australia

Table E1: Climate match scores for exotic finfish species introduced to Australia: (A) successfully introduced, (B) unsuccessfully introduced (recorded but not known to be established). The column headed 10% is the number of grid squares (0.5^o latitude x longitude) in Australia within 10% of the mean ie the highest level of match possible in the CLIMATE program between the fish's overseas range and Australian locations. Successively higher percentage values represent lower levels of climate match. Climate Match Index (CMI) = 20(number of squares within 10% of the mean) + 10(20% of mean) + 5(30% of mean) + 2(20% of mean) + 1(50% of mean). Maps are presented in the Appendix Figure J1.

A: Successful species	**10%**	**20%**	**30%**	**40%**	**50%**	**CMI**
European carp *Cyprinus carpio*	0	56	263	508	1001	3892
Tench *Tinca tinca*	20	103	213	135	114	2879
Goldfish *Carassius auratus*	3	38	155	213	464	2105
Roach *Rutilus rutilus*	0	19	53	133	222	943
White-cloud mountain minnow *Tanichthys albonubes*	0	1	6	15	16	86
Mosquitofish *Gambusia holbrooki + G. affinis*	7	75	356	749	796	4964
Guppy *Poecilia reticulata*	0	0	108	487	787	2301
One-spot live bearer *Phalloceros caudimaculatus*	0	3	7	25	104	219
Sailfin molly *Poecilia latipinna*	0	16	133	190	626	1831
Platy *Xiphophorus maculatus*	0	3	18	108	208	544
Green swordtail *Xiphophorus hellerii*	12	54	104	272	567	2411
Mozambique tilapia *Oreochromis mossambicus*	3	102	362	611	813	4925
Red devil/Midas cichlid *Amphilophus citrinellus*	0	0	6	17	35	99
Three-spot cichlid *Cichlasoma trimaculatum*	0	9	56	103	124	700
Victoria Burton's haplochromine *Haplochromis burtoni*	0	0	0	14	78	106
Niger cichlid *Tilapia mariae*	0	0	0	7	13	27
Oscar *Astronotus ocellatus*	0	2	5	27	119	218
Blue acara *Aequidens pulcher*	0	0	0	10	51	71
Convict cichlid *Archocentrus nigrofasciatus*	0	5	49	89	94	567
Jewel cichlid *Hemichromis bimaculatus*[2]	0	15	143	272	335	1744
Redbelly tilapia *Tilapia zillii*	0	0	13	74	389	602
Jack dempsey *Cichlasoma octofasciatum*	0	12	64	136	182	894
Weather loach *Misgurnus anguillicaudatus*	0	0	1	16	81	118
Redfin perch *Perca fluviatilis*	0	16	43	73	101	622
Rainbow trout *Oncorhynchus mykiss*	0	53	299	839	781	4484
Brown trout *Salmo trutta*	1	22	63	155	334	1199

Brook trout *Salvelinus fontinalis*	0	0	0	4	54	62
Three-spot gourami *Trichogaster trichopterus*	0	14	105	183	297	1328
Yellowfin goby *Acanthogobius flavimanus*	0	0	2	19	39	87
Goby *Acentrogobius pflaumii*	0	0	2	4	28	46
Chameleon goby *Tridentiger trigonocephalus*	0	0	8	56	134	286
B: Unsuccessful species						
Rosy barb *Puntius conchonius*	0	2	156	372	462	2006
Sumatra barb *Puntius tetrazona*	0	0	0	0	0	0
Dominican Gambusia *Gambusia dominicensis*	0	0	0	3	15	21
Green terror *Aequidens rivulatus*	0	0	0	7	42	56
Firemouth cichlid *Thorichtys meeki*	0	5	55	116	136	693
Banded cichlid *Heros severus*	0	0	1	19	89	132
Redhead cichlid *Vieja synspila*	0	0	0	0	4	4
Pearl cichlid Geophagus brasiliensis	0	2	5	8	47	108
Blue tilapia *Oreochromis aureus*	0	0	5	106	472	709
Wami tilapia *Oreochromis urolepis*	0	4	17	108	293	634
Chinook salmon *Oncorhynchus tshawytscha*	0	0	2	19	52	100
Atlantic salmon *Salmo salar*	3	36	136	123	95	1441
Plainfin frogfish *Porichthys notatus*	0	0	8	29	97	195
Japanese seabass *Lateolabrax japonicus*	0	1	3	20	59	124
Sobaity seabream *Sparidentex hasta*	0	0	0	0	0	0
Common triplefin *Forsterygion lapillum*	4	10	21	15	53	368
Redbanded perch *Hypoplectrodes huntii*	4	11	21	16	56	383
American flagfish *Jordanella floridae*	0	0	0	2	7	11

Appendix F

Overseas range sizes and establishment success for finfish introduced to Australia

Table F1: Data on overseas range sizes[1] and introduction success[2] (excluding Australia) for exotic finfish species introduced to Australia: (A) successfully introduced, (B) unsuccessfully introduced (recorded but not known to be established). (Data collated from Fishbase 2004).

A. Successful species	Number of 1° (latitude x longitude) grid squares where fish recorded[1]	Number of successful overseas introduction events[3]	Total number of overseas introduction events[4]	Proportion of overseas introduction events that are successful[2]
European carp *Cyprinus carpio*	145	79	85	0.93
Tench *Tinca tinca*	22	17	21	0.81
Goldfish *Carassius auratus*	146	53	55	0.96
Roach *Rutilus rutilus*	38	5	6	0.83
White-cloud mountain minnow *Tanichthys albonubes*	64	2	2	1.00
Mosquitofish *Gambusia holbrooki + G. affinis*	129	68	70	0.97
Guppy *Poecilia reticulata*	39	34	36	0.94
One-spot live bearer *Phalloceros caudimaculatus*	25	1	1	1.00
Sailfin molly *Poecilia latipinna*	18	8	8	1.00
Platy *Xiphophorus maculatus*	18	9	9	1.00
Green swordtail *Xiphophorus hellerii*	10	18	18	1.00
Mozambique tilapia *Oreochromis mossambicus*	134	73	80	0.91
Red devil/Midas cichlid *Amphilophus citrinellus*	14	1	1	1.00
Three-spot cichlid *Cichlasoma trimaculatum*	13	0	1	0
Victoria Burton's haplochromine *Haplochromis burtoni*	5	0	0	-
Niger cichlid *Tilapia mariae*	25	1	1	1.00
Oscar *Astronotus ocellatus*	32	5	6	0.83
Blue acara *Aequidens pulcher*	12	1	2	0.50
Convict cichlid *Archocentrus nigrofasciatus*	3	2	2	1.00
Jewel cichlid *Hemichromis bimaculatus*	29	2	2	1.00
Redbelly tilapia *Tilapia zillii*[2]	49	11	15	0.73
Jack dempsey *Cichlasoma octofasciatum*	8	2	2	1.00

Weather loach *Misgurnus anguillicaudatus*	20	5	5	1.00
Redfin perch *Perca fluviatilis*	30	7	7	1.00
Rainbow trout *Oncorhynchus mykiss*	194	52	65	0.80
Brown trout *Salmo trutta*	82	24	33	0.73
Brook trout *Salvelinus fontinalis*	199	26	37	0.70
Three-spot gourami *Trichogaster trichopterus*	95	6	7	0.86
Yellowfin goby *Acanthogobius flavimanus*	6	2	2	1.00
Goby *Acentrogobius pflaumii*	3	0	0	-
Chameleon goby *Tridentiger trigonocephalus*	7	1	1	1.00
B. Unsuccessful species				
Rosy barb *Puntius conchonius*	29	4	5	0.80
Sumatra barb *Puntius tetrazona*	1	2	3	0.67
Dominican Gambusia *Gambusia dominicensis*	2	0	0	-
Green terror *Aequidens rivulatus*	10	0	0	-
Firemouth cichlid *Thorichtys meeki*	4	4	5	0.80
Banded cichlid *Heros severus*	12	0	1	0
Redhead cichlid *Vieja synspila*	85	0	0	-
Pearl cichlid Geophagus brasiliensis	7	0	1	0
Blue tilapia *Oreochromis aureus*	21	19	25	0.76
Wami tilapia *Oreochromis urolepis*	9	9	9	1.00
Chinook salmon *Oncorhynchus tshawytscha*	110	2	14	0.14
Atlantic salmon *Salmo salar*	80	4	16	0.25
Plainfin frogfish *Porichthys notatus*	39	0	0	-
Japanese seabass *Lateolabrax japonicus*	18	0	0	-
Sobaity seabream *Sparidentex hasta*	2	0	0	-
Common triplefin *Forsterygion lapillum*	4	0	0	-
Redbanded perch *Hypoplectrodes huntii*	1	0	0	-
American flagfish *Jordanella floridae*	2	0	0	-

[1] Fishbase (2004) occurrence records do not cover include the full geographic range of most species, hence these indices of overseas range size will underestimate the distribution of most species. Fishbase (2004) also often has multiple occurrence records from a single site or from sites close together. Therefore the number of one-degree latitude by one-degree longitude grid squares which contained

Table F1 cont.

occurrence record(s) were considered to give a better index of overseas range size than the total number of occurrence records for a species. Latitude by longitude squares cover a larger area of land near the equator compared to near the poles. It would be possible to create an excel spreadsheet to convert the latitude by longitude grid squares totals presented in the table to equivalent land areas to correct this potential source of bias. This was not done in the current project because of time limitations (typing in thousands of records) and because it was assumed that any bias would be equivalent across both successfully and unsuccessfully introduced fishes.

[2] The value in column three divided by the value in column 4.

[3] Number of overseas introductions (outside endemic range and excluding Australian introductions) that are considered to have been successful (ie led to an exotic population establishing). Data are collated from FishBase (2004) and exclude introduction records for which establishment outcomes are recorded as uncertain.

[4] Total number of overseas introductions (outside endemic range and excluding Australian introductions) including both known successful and known unsuccessful introduction records. Data are collated from FishBase (2004) and exclude introduction records for which establishment outcomes are recorded as uncertain.

Appendix G

Factors affecting establishment success of exotic aquarium fish introduced to Australia

Table G1. Establishment risk scores for exotic aquarium finfish species introduced to Australia. **A.** Successfully introduced. **B.** Unsuccessfully introduced (recorded but not known to be established).

A: Successfully introduced species	Climate match score 0–8	Overseas range score 0–4	Establishment Score 0–3	Introduction success score 0–4	Taxa risk score 0–5
European carp *Cyprinus carpio*	7	4	3	4	5
Goldfish *Carassius auratus*	5	4	3	4	5
White-cloud mountain minnow *Tanichthys albonubes*	1	4	2	4	3
Mosquitofish *Gambusia holbrooki + affinis*[2]	8	4	3	4	5
Guppy *Poecilia reticulata*	5	4	3	4	5
One-spot live bearer *Phalloceros caudimaculatus*	3	3	2	4	5
Sailfin molly *Poecilia latipinna*	5	2	3	4	5
Platy *Xiphophorus maculatus*	4	2	3	4	5
Green swordtail *Xiphophorus hellerii*	5	1	3	4	5
Red devil/Midas cichlid *Amphilophus citrinellus*	1	2	2	4	3

Table G1 cont.

Three-spot cichlid *Cichlasoma trimaculatum*	4	2	0	0	4
Victoria Burton's haplochromine *Haplochromis burtoni*	2	0	1	2	3
Niger cichlid *Tilapia mariae*	1	3	2	4	4
Oscar *Astronotus ocellatus*	3	4	3	4	5
Blue acara *Aequidens pulcher*[3]	1	2	2	2	3
Convict cichlid *Archocentrus nigrofasciatus*	4	0	2	4	4
Jewel cichlid *Hemichromis bimaculatus*[3]	5	3	2	4	5
Redbelly tilapia *Tilapia zillii*[3]	4	4	3	3	4
Jack dempsey *Cichlasoma octofasciatum*[4]	4	2	3	4	4
Weather loach *Misgurnus anguillicaudatus*	2	2	3	4	5
Three-spot gourami *Trichogaster trichopterus*	5	4	3	4	5
Chameleon goby *Tridentiger trigonocephalus*[5]	3	1	2	4	5
Mean successful (standard deviation)	**3.7 (1.9)**	**2.6 (1.3)**	**2.4 (0.8)**	**3.6 (1.0)**	**4.4 (0.8)**

[1] Listed by in Kailola (2000) as 'established' unless otherwise indicated below.

[2] Although *Gambusia affinis* and *G. holbrooki* are now recognized as separate species, with only *G. holbrooki* known to be established in Australia, *G. holbrooki* was once considered to be a sub-species of *G. affinis* and it is clear that Fishbase records do not accurately separate the two taxa according to their current classification

[3] Listed by Mark Lintermans (in prep.) as 'established' in Australia.

[4] Listed by Mark Lintermans (pers. comm. 8 April 2004) as 'established' in Australia.

[5] Listed by Howard Gill (pers. comm. 15 April 2004) as 'established' in Australia.

Table G1 cont.

B: Unsuccessfully introduced species	Climate match score 0–8	Overseas range score 0–4	Establishment score 0–3	Introduction success score 0–4	Taxa risk score 0–5
Rosy barb *Puntius conchonius*	5	3	3	4	5
Sumatra barb *Puntius tetrazona*	0	0	3	3	5
Dominican Gambusia *Gambusia dominicensis*[4,5]	1	0	1	2	5
Green terror *Aequidens rivulatus*	1	1	1	2	3
Firemouth cichlid *Thorichtys meeki*	4	0	3	4	4
Banded cichlid *Heros severus*	2	2	0	0	4
Redhead cichlid *Vieja synspila*	0	4	1	2	4
Pearl cichlid *Geophagus brasiliensis*	2	1	0	0	3
Blue tilapia *Oreochromis aureus*[2]	4	3	3	4	4
Wami tilapia *Oreochromis urolepis*[3]	4	1	3	4	4
American flagfish *Jordanella floridae*[4]	1	0	1	2	5
Mean unsuccessful (standard deviation)	**2.2 (1.8)**	**1.4 (1.4)**	**1.7 (1.3)**	**2.5 (1.5)**	**4.2 (0.8)**

[1] Listed by in Kailola (2000) as ‘recorded’ but not known to be established, or only maintained by repeated artificial releases, unless otherwise indicated below.

[2] Listed by Lever (1996) as ‘recorded’ in Australia.

[3] Listed by Welcomme (1988) as ‘recorded’ in Australia

[4] Listed by McKay (1984) as ‘recorded’ in Australia

[5] Listed in Fishbase (2004) as ‘recorded’ in Australia.

Appendix H

Establishment risk scores for 27 exotic pest fishes

Fishbase (2004) lists 27 species of exotic fish that have been reported by one or more countries as having adverse ecological impacts. The establishment risk scores for these 27 species have been calculated (Table H1) and all 27 species score in the high-extreme establishment risk range for Australia, with the single exception of the bighead carp *Aristichthys nobilis* which scores a moderate risk. Climate match maps and data for 17 of the 27 species are presented in Appendix J, Figure J2, and the remaining 10 climate match maps and data (for species that have been introduced to Australia) are presented in Apendix J, Figure J1.

Table H1. Establishment risk scores for the 27 exotic fish species that are listed in Fishbase (2004) as being reported by one or more countries as having adverse ecological impacts.

27 pest species from Fishbase	Climate match score 0–8	Overseas range score 0–4	Establish-ment Score 0–3	Introduction success score 0–4	Taxa risk score 0–5	Establishment Risk Score 0–24	Establish-ment Risk Rank
European carp *Cyprinus carpio*	7	4	3	4	5	23	Extreme
Rainbow trout *Oncorhynchus mykiss*	8	4	3	4	3	22	Extreme
Mozambique tilapia *Oreochromis mossambicus*	8	4	3	4	4	23	Extreme

Table H1 cont.

Nile tilapia *Oreochromis niloticus niloticus*	8	4	3	4	4	23	Extreme
Stone moroko *Pseudorasbora parva*	5	4	3	4	5	21	Extreme
Brown trout *Salmo trutta*	5	4	3	4	4	20	Very high
Black bullhead *Ameiurus melas*	5	4	3	4	5	21	Extreme
Silver carp *Hypophthalmichthys molitrix*	4	2	3	3	2	14	High
Pumpkinseed *Lepomis gibbosus*	4	4	3	4	5	20	Very high
Largemouth bass *Micropterus salmoides*	8	4	3	4	4	23	Extreme
Guppy *Poecilia reticulata*	5	4	3	4	5	21	Extreme
Mosquitofish *Gambusia holbrooki + G. affinis*	8	4	3	4	5	24	Extreme
Goldfish *Carassius auratus*	5	4	3	4	5	21	Extreme
Bluegill *Lepomis macrochirus*	8	4	3	4	5	24	Extreme
Round goby *Neogobius melanostomus*	3	2	3	4	5	17	High
Walking catfish *Clarias batrachus*	5	4	2	4	3	18	Very high
Zander *Sander lucioperca*	2	2	2	4	5	15	High
Bighead carp *Aristichthys nobilis*	2	1	3	2	2	10	Moderate
Grass carp *Ctenopharyngodon idella*	4	3	3	2	1	13	High
Ruffe *Gymnocephalus cernuus*	0	2	3	4	5	14	High
Sharpbelly *Hemiculter leucisculus*	2	2	2	4	5	15	High
Lake Tanganyika sardine *Limnothrissa miodon*	5	1	2	4	5	17	High
Pejerrey *Odontesthes bonariensis*	1	0	3	4	5	13	High
Redfin perch *Perca fluviatilis*	4	3	3	4	5	19	Very high
Flathead minnow *Pimephales promelas*	2	4	3	4	4	17	High
Sailfin molly *Poecilia latipinna*	5	2	3	4	5	19	Very high
Green swordtail *Xiphophorus helleri*	5	1	3	4	5	18	Very high

Appendix I

Definition of terms

The following definitions have been attributed to the various components and stages of invasion (modified from Cassey and Arthington 1999):

A **non-native, non-indigenous** or **exotic species** is defined as one that is not native (indigenous) to the country under discussion, while an **indigenous** species is one which is native to that country. The term **introduced** is used more generally to refer to any species intentionally or accidentally released into an environment outside its natural range (Welcomme 1988).

Translocation refers to the movement of indigenous species to areas beyond their natural range but within the country of origin, and the movement of established exotic species to a new area. Welcomme (1988) used the terms **transferred** and **transplanted** to describe any species intentionally or accidentally transported and released within its previously described range, to enhance populations under stress or in decline, to introduce new genotypes or genetic diversity into a local stock, or to re-establish a species which has become locally extinct.

A **colonising species** is one that habitually establishes itself in transient or disturbed Habitats. True **invaders** are not confined to disturbed habitats, colonisers are therefore a subset of invaders specialising in disturbed situations.

An **established** or **naturalised** species is one which has formed a self-sustaining population, which persists through local reproduction and recruitment.

Invasion is the geographical expansion of a species' range into an area not previously occupied by that species (Vermeij 1996). Within the literature invaders have been variously termed aliens, immigrants, exotics, adventives, neophytes, xenophytes, or simply introduced species. Invaders may be native to the region or country but not to the community in question.

A **pest** is any species, though often an exotic species, that has a negative economic, social or ecological impact (Williamson 1996).

A **propagule** is the unit, or number of individuals, involved in each introduction or invasion event. MacArthur and Wilson (1967) used propagule to describe the minimum number of individuals of a species capable of successfully establishing in a given environment. In a successful invasion a single pregnant female, an adult female and a male, or a whole social group may be propagules, providing they are the minimal unit required for establishment (MacArthur and Wilson 1967).

Propagule pressure is the effect on the probability of successful invasion of increasing or decreasing the size and the number of propagules.

Persistence (or **integration**) occurs when the invading species forges ecological links with other species in the recipient region, and evolution occurs, reflecting the changed selective regime in the recipient community (Vermeij 1996). Integration involves changes in the recipient ecosystem during and following an invasion.