BIODIVERSITY REVIEW

Alien freshwater fishes in Brazilian aquaculture and sport fishing: reviewing their economic benefits and risks to native fish diversity

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Running title: Risks from alien freshwater fishes in Brazil

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ABSTRACT

Aim: To review the use and value of alien freshwater fishes in Brazilian aquaculture and recreational angling, their ecological risks in the environment and the empirical evidence on their impacts on native fish diversity.

Location: Brazil and the Neotropical Region.

Methods: Literature review, analysis of relevant databases on aquaculture and freshwater fish introductions, and use of the Fish Invasiveness Scoring Kit (FISK).

Results: The use of alien freshwater fishes in aquaculture and angling in Brazil specifically, and the Neotropical Region generally, has never been subject to ecological risk assessment processes. Today, alien fishes comprise a substantial proportion of total aquaculture production and value in Brazil, contributing over $US 250 million in 2008 (63 % of the total value of freshwater aquaculture). The alien fishes that are used most prominently are *Cyprinus carpio* and *Orecohromis niloticus*; ecological risk assessment and literature review suggest both species are potentially highly invasive and may affect the ecological integrity of invaded water bodies. Peacock basses (*Cichla* species) have been introduced from Amazonia into other Brazilian river basins for creation of recreational fisheries. Introductions generally result in establishment and invasion, and significant and rapid declines in native fish diversity have been subsequently reported in a number of studies.

Main conclusions: Alien freshwater fishes in Brazilian aquaculture and sport fishing support ecosystem services of economic value, but the principal species used represent high ecological risks, with empirical studies revealing deleterious impacts on native fishes, including extinctions. It is thus recommended that risk assessment and risk management processes on alien fishes are implemented in Brazil and the

Neotropical Region to minimise the threat of further harmful introductions, in conjunction with the continued development and support of aquaculture systems based on indigenous fishes.

Keywords: *Cichla kelberi*, *Oreochromis niloticus*, risk assessment, invasion, non-indigenous.

INTRODUCTION

The ecosystem services of freshwater aquaculture and recreational angling have the capacity to generate significant economic returns, support recreational activities with substantial societal benefits, and play an important role in global food production (Pitcher, 1999; Ross *et al*., 2008). For example, global freshwater fish aquaculture production in 2009 exceeded 73 million tonnes, worth approximately $US 61 billion (FAO, 2011a). Although similar global figures are not available for recreational angling, national figures suggest it supports significant regional and national economies, with an estimated combined annual expenditure in ten countries in Western Europe during the 1990s of $US 10 billion (Cowx, 1998). Both aquaculture and angling have a tendency to rely on alien fishes to enhance production and/ or fishery performance (Casal, 2006; Gozlan, 2008; Gozlan *et al*., 2010). Globally, species such as rainbow trout *Oncorhyncus mykiss*, common carp *Cyprinus carpio* and Nile tilapia *Oreochromis niloticus* are now present in many countries having been introduced for these purposes (Casal, 2006; Zambrano *et al*., 2006; Vitule *et al*., 2009). Indeed, fishes are among the most introduced group of aquatic animals in the world (Gozlan, 2008), with aquaculture (51 % of all introductions) and angling (12 % of all introductions) providing major introduction pathways (Gozlan *et al*., 2010).

The fish diversity of Brazilian freshwaters has high global significance; by 2003, at least 2122 fishes were catalogued (21 % of the world list; Agostinho *et al*. 2005). Moreover, fish assemblages in isolated river basins tend to comprise of high proportions of endemic fishes (Agostinho *et al*., 2005) and it has been argued that as much as 40 % of Neotropical freshwater fishes have yet to be described (Reis *et al*., 2003). A proportion of these fishes are, however, threatened; Agostinho *et al*. (2005) discussed factors that were causing threats to 134 species and these included river impoundments, fishery exploitation and introductions of alien species. These were most apparent in the more developed regions of Brazil, particularly those in the south and southeast (Agostinho *et al*., 2005). Reservoirs have been built in the majority of Brazilian hydrographic basins and these have profoundly influenced the composition and structure of the fish assemblages (Agostinho *et al*., 2007, 2008). For example, comparisons of assemblage pre- and post dam construction generally show substantial losses of migratory species with replacement by sedentary species (Gubiani *et al*., 2010). Where previously impassable barriers to fish movement have been overcome by water inundation then this has also enabled the movement of many fishes into previously isolated watersheds (Júlio Júnior *et al*., 2009).

It is against this background of substantial environmental and habitat modification through impoundment that the influence of alien species in aquaculture and recreational angling on freshwater fish diversity in Brazil has to be assessed. The formation of substantial areas of lentic water has enabled the development of new recreational fisheries and cage aquaculture systems in what were previously lotic waters (Agostinho *et al*., 2005). For example, in the upper Paraná River Basin, recreational fisheries have been created through introductions of peacock basses - fishes of the *Cichla* genus - including *Cichla kelberi*, *Cichla piquiti* and *Cichla monoculus* (Latini & Petrere, 2004; Viera *et al*., 2009). Cage aquaculture systems have developed that frequently utilise species such as *Oreochromis niloticus* (Zambrano *et al*., 2006; Vitule *et al*., 2009). From a conservation perspective, the precautionary approach would suggest it inappropriate to utilise these alien fishes in this manner (Leprieur *et al*., 2009; Vitule *et al*., 2009). However, of the numerous freshwater fishes that have been introduced into areas outside of their natural range, establishment rates have been relatively low and few species have had measureable ecological impacts (Gozlan, 2008). Instead, many introduced fishes have provided considerable societal and economic benefits (Gozlan *et al*., 2010). Consequently, it can be argued that policy formulation and management of alien fishes in the environment requires evidence-based science on which to base decisions, rather than relying on precaution (Britton *et al*., 2011a,b).

The use of alien freshwater fishes in aquaculture and angling in Brazil specifically, and the Neotropical Region more generally, has previously never been subject to ecological risk assessment processes (Agostinho *et al*., 2005; Darrigran *et al*., 2011). Although less satisfactory, risk assessment can be used in post-introduction phases as this can help inform subsequent management approaches (Britton *et al*., 2011a). When used in combination with published empirical studies on their impacts, *a posteriori* assessments of alien fishes can be compared with the economic benefits they have accrued. Thus, the aim of this review was to identify the utilisation and value of alien fishes in Brazilian freshwater aquaculture and recreational angling, utilise risk assessment techniques to predict the ecological risks of these fishes, review empirical studies to evaluate their actual impacts on fish diversity, and finally evaluate their continued use in these ecosystem services.

MATERIALS AND METHODS

Open-access and independently-collected databases were searched to identify the alien freshwater fishes currently present in Brazil, their introduction pathways (aquaculture, angling or other), and their production levels and values. The databases were those relating aquaculture (Food and Agriculture Organisation FAO; http://www.fao.org/fi/statist/statit.asp) and fish introductions (FishBase http://www.fishbase.org; Global Invasive Species Database http://www.issg.org/database/welcome/). All were accessed on 17/04/2011.

Assessments of the ecological risks associated with the alien fishes in Brazilian freshwaters were completed using 2 methods. Firstly, scores were used from the Fish Invasiveness Scoring Kit (FISK; CEFAS, 2011), where scores were already available for the majority of the alien fishes and where a score > 19 indicates a high risk of invasiveness (*cf.* Copp *et al.*, 2009; Britton *et al.*, 2010). Although primarily developed for use in the UK and Western Europe (Copp *et al.*, 2005), the toolkit has wider application in assessing the ecological risks associated with introduced fishes elsewhere (Copp *et al.*, 2009). Where scores were not available for a species, FISK was utilised by the authors and an assessment completed as per Copp *et al.* (2009). Secondly, assessments were made as per Gozlan (2010), where the likelihood of an alien fish invoking ecological impacts in the environment was assessed from literature reviews. Impact was defined as a negative consequence in a native ecosystem that is quantifiable and has resulted in habitat degradation, competition with native species for spawning ground, hybridisation threatening species integrity and/or predation on native species populations, resulting in their decline (Gozlan, 2010). Similar to FISK, for a number of the alien fishes present in Brazil, impact likelihood values (as the percentage of studies where impact was detected) were already present in Gozlan (2010); where these were absent then the reviews were completed by the authors.

Finally, reviews (case studies) on two groups of alien fishes present in Brazilian freshwater aquaculture and angling were developed, with the reviewed fishes those that were assessed as having the potential to cause ecological impacts. The reviews were designed to identify whether empirical evidence was available from field studies to corroborate the assessed risks. This then enabled the empirical information to be compared against as the value of these alien fishes in supporting the ecosystem services so that their overall benefits to Brazil could be evaluated.

RESULTS

Alien freshwater fishes in Brazil

There at least 15 alien freshwater fishes present in Brazil that are associated with the aquaculture trade or angling (Table 1); in the case *Cichla* species, these have been introduced into impoundments in the south and southeast of the country from Amazonia for creating angling opportunities and so represent a translocation within the country rather than an introduction *sensu stricto*. Not included on the list are at least 33 other fishes that have dispersed across watersheds as a consequence of dam and reservoir construction that flooded a previously impenetrable barrier (*cf.* Júlio Júnior *et al*., 2009). In the case of the African catfish *Clarias gariepinus*, Vitule *et al*. (2006) suggested their recording in Southern Brazil was a consequence of escapees from lakes used for recreational angling, although they have also been used in pond aquaculture since at least 1995 (FAO, 2011b). Compared with the native fish diversity of the country, the extent of the fish allodiversity resulting from aquaculture and angling appears relatively low, comprising of only six families (Table 1).

Freshwater fish and alien fish aquaculture production and value in Brazil

The reported total freshwater fish aquaculture production has been generally increased year-on-year in Brazil since recorded data were first available in 1995, with substantial increases in the late 1990s and early 2000s (Fig. 1). In the last 2 years for which data were available (2007 and 2008), total production was 209,812 and 210,906 tonnes respectively. The production increases are reflected in their economic value (Fig. 1); in 2007 and 2008, the total value of freshwater fish aquaculture in Brazil was $US 397 million and $US 399 million respectively.

Of the species being cultured, the FAO statistics provide breakdowns for some species but amalgamate values for others. Of the alien fish that feature, the annual contribution of *C. carpio* to total aquaculture production between 1995 and 2008 has ranged from 17 to 46 %, and in value from 10 to 30 % (Fig. 1). Their annual production and economic value decreased through the 2000s. Data on the production and value of tilapia species in aquaculture have been combined for all the species, making it impossible to differentiate between alien and indigenous species. According to Vitule *et al*. (2009), however, *O. niloticus* are the principal tilapia used in Brazilian aquaculture. Thus, assuming that the majority of cultured tilapias are *O. niloticus*, then their contribution to total annual production and value has generally increased year-on-year since 1995 (Fig. 1). Their annual contribution to total aquaculture production between 1995 and 2008 ranged from 22 to 45 %, and in value from 30 to 51 %. Of other alien fishes that are mentioned specifically in the statistics, *O. mykiss*, *C. gariepinus* and *I. punctatus* never contributed more than 6 % by production and 7 % by value to the annual statistics in the period and their combined contributions in 2008 were only 2.0 and 2.4 % respectively. Asian cyprinid species such as bighead carp *Hypophthalmichthys molitrix* and grass carp *Ctenopharyngodon idella* are utilised within Brazilian aquaculture but their specific production values are not provided and so are assumed to be insignificant (FAO, 2011b).

In combination, between 1995 and 2008, alien fishes contributed between 62 and 80 % of total annual aquaculture production, and between 61 and 76 % of total annual value. Thus, freshwater fish aquaculture production in Brazil is highly dependent upon alien fishes.

Value of recreational freshwater angling and the associated use of alien fishes in Brazil

The practice of introducing alien fishes to enhance angling in impoundments has been a widespread activity in some areas of Brazil, such as the Upper Paraná basin where it was widespread until at least 1990 (Agostinho *et al*., 2007); species such as *C. kelberi* and *C. piquiti* were introduced for the creation of sport fishing opportunities as both were valued for their fighting qualities (Espínola *et al*., 2010). Although there are no available data relating to the economic value of using alien fishes in Brazilian fisheries, Holley *et al*. (2008) discussed the value of the indigenous peacock bass fishery of the Rio Negro River in Amazonia. Up to 1800 anglers are attracted to the region annually who spend up to $US 6 million (Holley *et al*., 2008). A study in the Brazilian Pantanal provided estimates of the value of recreational fishing to the region; the total annual welfare measure due to recreational fishing was estimated as ranging from $US 35 to 56 million (Shrestha *et al*., 2002). Although there was no suggestion this fishery was exploiting alien fishes, it does demonstrate that recreational anglers in Brazil are prepared to expend significant outlays on angling (Shrestha *et al*., 2002). Thus, a successful fishery based on alien fishes may have the potential to generate significant economic income.

Ecological risk assessments of alien fishes in Brazil

According to Gozlan (2008), alien fishes that represent good candidates for use in freshwater aquaculture are those that generate considerable economic values but have minimum ecological consequences should they escape into the environment. In the case of alien fishes in Brazilian freshwater aquaculture, only *C. carpio* and *O. niloticus* generate substantial production and economic values (Fig. 1) but their FISK scores suggest a high degree of invasiveness (Fig. 2a). Their values of likelihoods of ecological impacts (Gozlan, 2010) suggest that whilst empirical evidence is less severe for *C. carpio*, for *O. niloticus*, invasion subsequent negative ecological impacts remain likely (Fig. 2b). Of the other alien fishes used in Brazilian aquaculture, *O. mykiss*, *I. punctatus* and *C. gariepinus* may represent better candidates due to their lower ecological risks (Fig. 2a,b) but all are currently of low economic value.

In order to identify whether any other alien freshwater fishes being used across South American aquaculture may be appropriate to use in Brazil on the basis of their economic value versus ecological risk, data were collated for the continent from the FAO database (Fig. 2). According to FISK scores, there are no alien fishes that represented a strong candidate for use; all high economic value species were associated with high scores (i.e. a high potential for invasiveness) (Fig. 2a). By contrast, rainbow trout were shown to have a relatively low likelihood of ecological impact (Gozlan, 2010) and generated significant economic values (Fig. 2b). However, given their current low use in Brazil and their requirements of relatively cool, well oxygenated water for production (FAO, 2011c), then it is unlikely there is scope for any increase in production in Brazil due to the prevailing warm water conditions.

The analysis of comparing economic values against potential invasiveness and likelihood of ecological impacts could not be completed for the *Cichla* species and *Micropterus salmoides* used in fishery enhancement (Table 1). A FISK score was, however, generated for the *Cichla* genus and the score (28.8) suggested a relatively high risk of invasiveness and impact. Their likelihood of causing ecological impact was also high, with no studies reporting negligible impact (*cf.* case study 1). Regarding *M. salmoides*, their mean FISK score of 15.5 in Copp *et al*. (2009) suggests their ability to invade is relatively low compared with *Cichla* fishes. Notwithstanding, empirical evidence on their likelihood of causing deleterious impacts on native fishes would appear high due to the high number of studies reporting negative consequences arising from their invasion (e.g., Cambray & Stuart, 1985; Werner *et al*., 1983; Werner & Hall, 1988). For example, Gratwicke & Marshall (2001) reported a 99 %

population decline in fishes of the Cyprinidae family in farm dams in Zimbabwe when *M. salmoides* was present.

Thus, it is apparent that the alien freshwater fishes most widely used in aquaculture (*C. carpio*, *O. niloticus*) and recreational angling (*Cichla* species) in Brazil were assessed as presenting considerable ecological risks, with high potential for invasive populations developing. For *Cichla* species and *O. nilocticus*, published empirical studies on their introductions are reviewed to reveal whether actual impacts on native fishes have been reported. For information on the ecological impacts of alien *C. carpio*, see recent reviews by Weber & Brown (2009) and Cucherousset & Olden (2011).

Case study 1: Peacock basses (*Cichla* genus)

Indigenous to Amazonia, peacock basses have been introduced across the Neotropical Region where they have been described as an underestimated threat to native fish communities (Pelicice & Agostinho, 2009). They are now widespread in many Brazilian reservoirs, such as those in the Upper Paraná River basin, following introductions for fishery creation (Espínola *et al.*, 2010). Introductions have generally been successful in producing sustainable stocks for angling exploitation (Agostinho *et al.*, 2007) and their populations tend to integrate successfully into the fish assemblage (Paiva *et al.*, 1994; Oliveira *et al.*, 2006; Pelicice & Agostinho, 2009). The invasiveness of *C. kelberi* is demonstrated by their subsequent wide dispersal throughout the Upper Paraná River basin following initial introductions (Kullander & Ferreira, 2006). Espínola *et al.* (2010) suggested it was the largest, deepest, most transparent and warmest reservoirs that were most likely to be colonised. Data on their invasive genetics, diet, parasitology, reproductive traits and growth rates are now available in a number of studies from across their extended range in Brazil (e.g., Oliveira *et al*., 2006; Resende *et al*., 2008; Martins *et al*., 2009; Vieira *et al*., 2009; Gomiero *et al*., 2010a,b; Yamada *et al*., 2011).

Peacock basses have been described as exceptionally voracious predators and it is this that has raised concern over their impacts on native fishes (Santos *et al*., 1994). Their piscivory has been described as seriously threatening native fish diversity (Godinho *et al*., 1994), acting as a major force of biotic homogenisation (Latini & Petrere, 2004). Moreover, there is compelling evidence from empirical studies to support this. For example, in a study conducted in the Roasna Reservoir in the Paraná River basin, *C. kelberi* was introduced in 2004 (Pelicice & Agostinho, 2009). Comparison of samples collected before (2003) and after introduction (2007) revealed that in their presence, native fish diversity was significantly impacted; mean fish density reduced by 95 % and species richness by 100 %. There was the complete disappearance of many smaller fish species. It was predicted that complete assemblage extinction could occur by 2010. Introductions of *C. monoculus* into lakes in the River Doce basin also resulted in reduced native fish richness and diversity of the community (Latini & Petrere, 2004). Other studies have shown deleterious impacts by *C. kelberi* on prey fishes were not prevented by vegetation, with aquatic plants providing minimal refugia for prey fishes (Kovalenko *et al*., 2010a). The vulnerability of native prey fishes to predation is also not due to a lack of recognition of *C. kelberi* as a predator, for anti-predator responses to a native fish predator and *C. kelberi* were similar (Kovalenko *et al*., 2010b).

In summary, introductions of peacock bass into freshwaters waters across Brazil specifically and the Neotropical Region generally tend to result in invasions, with invasive populations then having substantial deleterious impacts on native fishes, affecting diversity and leading to biotic homogenisation.

Case study 2: *Oreochromis niloticus*

Oreochromis niloticus is commonly used in aquaculture across the world as the species represents a robust culture fish through their physiological tolerances and ability to withstand variable water chemistry, in conjunction with their production and husbandry being facilitated by their traits of multiple spawning, parental care, and high dietary plasticity (Attayde *et al*., 2007; Freire & Prodocimo, 2007). Vitule *et al*. (2009) describe *O. niloticus* as the principal tilapia used in Brazilian aquaculture. Introductions into the environment are usually associated with releases from aquaculture facilities (Peterson *et al*., 2005; Strecker, 2006; McCrary *et al*., 2007) and following an introduction, should ambient conditions be suitable, then invasive populations can form rapidly (Weyl, 2006). Zambrano *et al*. (2006) suggested that suitable habitats for *O. niloticus* invasions were present across much of South America and particularly in Brazil.

In freshwater habitats where *O. niloticus* develops invasive populations, native species have been reported to be directly and adversely impacted through decreased abundance and even extinctions (Weyl, 2006). These result from overlaps in habitat and resource utilisation, and competition for spawning sites (Peterson *et al*., 2004, 2005; Canonico *et al*., 2005; Vitule *et al*., 2009). Indirect impacts on native fishes include modifications to habitat and water quality, including turbidity (Figueredo &

Giani, 2005). Hybridisation with native *Oreochromis* species is also possible (Moralee *et al*., 2000). Vitule *et al*. (2009) discussed the deleterious effect of *O. niloticus* on the native fish fauna of Brazil and described their adverse effects on the community structure of native fishes, their impacts in reducing the abundance of planktonic microcrustaceans and the lowering of water transparency through increased abundance of microalgae (Gurgel & Fernando, 1994; Attayde *et al*., 2007; Okun *et al*., 2008). The associated release of high quantities of nutrients into the environment from *O. niloticus* cage aquaculture systems has also been shown to result in local elevations in the availability of zooplankton which has been demonstrated to invoke changes in the feeding and diet of native zooplanktivorous fish (Strictar-Pereira *et al*., 2010).

In summary, whilst the influence of *O. niloticus* on native fish diversity may not appear as profound as *Cichla* species, empirical evidence does also suggest substantial impacts on native fish abundance and richness, and indirect impacts on fish communities that include habitat modification and shifts in water quality.

DISCUSSION

Freshwater fish diversity in many river basins in Brazil has been adversely impacted by reservoir construction; substantial changes to habitats, blockage of migratory routes, disruptions to ecosystem functioning and major changes in native fish assemblages have been recorded and this is irrespective of alien fish introductions (Agostinho *et al*., 2005, 2007, 2008; Júlio Júnior *et al*., 2009; Gubiani *et al*., 2010). However, following reservoir construction, high-value aquaculture and angling opportunities have been created in the new lentic habitats in which alien fishes feature prominently (Pelicice & Agostinho, 2009; Vitule *et al*., 2009). Their use has thus provided substantial societal and economic benefits; for example, the total value of alien fishes in Brazilian freshwater aquaculture was in excess of $US 250 million in 2008 (FAO, 2011b). This benefit may come, however, with an ecological and conservation cost to native fishes. This is because the alien fishes most used in these activities were assessed as having traits that provide them with a high degree of invasiveness. Empirical studies validated this. Peacock basses have been described as a voracious predator acting as a major force of biotic homogenisation (*cf*. Case study 1). The effect of Nile tilapia on native fishes was direct through competition and indirect through changes in water quality and habitat (*cf*. Case study 2). There are also numerous empirical studies and reviews available on negative impacts of invasive *C. carpio* populations (e.g., Weber & Brown, 2009; Cucherousset & Olden, 2011).

Thus, there is an apparent disparity between the societal and economic benefits accrued from using alien freshwater fishes in Brazilian aquaculture and angling, and the negative impacts they may incur on native fish diversity. As a consequence, identification of alternative management options to using these fishes is necessary that seek to reduce risk and impacts on native fishes but maintain benefits (Gozlan, 2008, 2010). Regarding aquaculture, then consideration of using an increased proportion of indigenous fishes is already being considered through development of 'technological packages' for native fishes with economical potential, such as tambaqui (*Colosomas* species) and surubin (*Pseudoplatistoma* species) (FAO, 2011a). This is allied to Ross *et al*. (2008) who argued that if aquaculture is to continue to expand in developing markets whilst minimising negative impacts from using alien fishes, then it must investigate increasing the cultivation of indigenous species. The situation of using peacock basses in sport angling is more complex in that introductions have already resulted in invasions and so non-indigenous populations are already widespread. Preventing further introductions is, thus, unlikely to minimise impacts on native fish diversity in river basins where they are already present and dispersing. The spatial scale at which the fishes are now present may make any form of population control virtually impossible, given that the ability to manage invasive fish in the environment is inversely related to the spatial extent of their dispersal (Britton *et al*., 2011b). To control and/ or eliminate peacock basses from invaded reservoirs may also require extensive ‘scorched-earth’ techniques such as piscicide application and this would be likely to incur substantial and unacceptable impacts on non-target native fishes (Britton *et al*., 2011b).

As it is apparent that managing the alien fishes already present in Brazilian freshwaters would be technically demanding, highly expensive and questionable as to its ability to succeed (Britton *et al*., 2011b), then their current status may have to be accepted. Management approaches could then focus on the implementation of risk assessment methodologies that aim to prevent introductions of new alien fishes and movements of non-indigenous fishes to areas outside of their existing ranges. Risk assessment procedures remain completely absent in decision making processes on alien fishes in Brazil (Agostinho *et al*., 2005, 2007, 2008). Given the development of risk assessment methodologies in the last decade elsewhere in the world (e.g., Copp *et al*., 2005, 2009; Britton *et al*., 2010, 2011a) then this can be remedied forthwith. Accordingly, to protect the native fish diversity of Brazilian freshwaters from the adverse effects of alien fish introductions, we recommend:

- Implementation of full risk assessment and risk management procedures when proposed introductions of non-indigenous fishes are made for both aquaculture and angling. Only species assessed as minimal risk to native fishes and their diversity should be considered for introduction to open systems;
- No new introductions of piscivorous non-indigenous fishes into Brazilian freshwaters for the creation and/ or enhancement of angling;
- Increased technological development of aquaculture systems for indigenous fishes, with support provided to aquaculturists to switch production from alien to indigenous fishes; and
- Formulation of consultative bodies comprising of all relevant stakeholders to assist implementation of the above recommendations, with the provision of information on the societal and economic benefits of using alien fishes in aquaculture and angling versus their ecological risk.

In summary, Brazil is a country with substantial diversity in native fish assemblages. This review has demonstrated that alien fishes do provide high societal and economic benefits in their utilisation in aquaculture and recreational angling, but this is currently to the detriment of native fish diversity and ecological integrity. Thus, if the native fish diversity across Brazil is to be maintained, then policies require implementing on alien fishes that seek to prevent their further biological homogenisation. Given the lack of risk based tools for alien fishes across the Neotropical Region more generally, then these policies will have application and relevance at this wider spatial scale.

ACKNOWLEDGEMENTS

The work was supported by Banco Santander (Britton) and Universidade Estadual de Londrina (Orsi). The views expressed in the paper are those of the authors and not their parent organisations.

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Table 1. Alien fishes recorded in Brazilian freshwaters, their introduction pathway and whether they were introduced from outside of Brazil or were translocated from within Brazil. Note the list does not include the movement of fish between watersheds occurring as a consequence of dam construction (*cf.* Júlio Júnior *et al*., 2009).

Species	Family	Introduction Pathway	Introduction or translocation
Micropterus salmoides	Centrarchidae	Angling	I
Cichla spp. (including *C. piquiti* and *C. kiberi*)	Cichlidae	Angling	T
Plagioscion squamosissimus	Cichlidae	Angling	T
Geophagus proximus	Cichlidae	Aquaculture	T
Ctenopharyngodon idella	Cyprinidae	Aquaculture	I
Cyprinus carpio	Cyprinidae	Aquaculture	I
Hypophthalmichthys molitrix	Cyprinidae	Aquaculture	I
Ictalurus punctatus	Ictaluridae	Aquaculture	I
Oncorhynchus mykiss	Salmonidae	Aquaculture	I
Oreochromis mossambicus	Cichlidae	Aquaculture	I
Oreochromis niloticus	Cichlidae	Aquaculture	I
Oreochromis urolepis hornorum	Cichlidae	Aquaculture	I
Tilapia rendalli	Cichlidae	Aquaculture	I
Clarias gariepinus	Clariidae	Aquaculture/ angling	I
Oreochromis aureus	Cichlidae	Aquaculture	I
Carassius auratus	Cyprinidae	Other	I
Xiphororus maculatus	Poeciliidae	Other	I
Lepomis cyanellus	Centrarchidae	Other	I
Apistogramma erythrura	Cichlidae	Other	I
Omobranchus punctatus	Blenniidae	Other	I
Betta splendens	Osphronemidae	Other	I

Figure captions

Figure 1. (a) Total annual freshwater fish aquaculture production (○) and the annual production of *Cyprinus carpio* (■) and tilapia species (□) in Brazil between 1995 and 2008. (b) Total annual freshwater fish aquaculture value (○) and the annual value of *Cyprinus carpio* (■) and tilapia species (□) in Brazil between 1995 and 2008.

Figure 2. (a) Economic value of freshwater fish aquaculture per alien species in South America in 2008 versus the FISK scores of the species (Copp *et al*., 2009; Birtton *et al*., 2010). (b) Economic value of freshwater fish aquaculture per alien species in South America in 2008 versus the likelihood of their ecological impact (Gozlan, 2010). Key: Cc *Cyrpinus carpio*; Cg *Clarias gariepinus*; On m *Oncorhynchus mykiss*; Ip *Ictalurus punctatus*; CI *Ctenopharyngodon idella*; Om *Oreochromis mossambicus*; On *Oreochromis niloticus*; Ar *Acipenser ruthenus*; Ab *Acipenser baeri*; St *Salmo trutta*; and Ss *Salmo salar*.

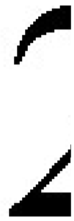

Figure 1.

Figure 2.