Article

Sena S. De Silva, Thuy T. T. Nguyen, Giovanni M. Turchini, Upali S. Amarasinghe and Nigel W. Abery

Alien Species in Aquaculture and Biodiversity: A Paradox in Food Production

Aquaculture is seen as an alternative to meeting the widening gap in global rising demand and decreasing supply for aquatic food products. Asia, the epicenter of the global aquaculture industry, accounts for over 90% of the global aquaculture production quantity and about 80% of the value. Asian aquaculture, as with global aquaculture, is dependent to a significant extent on alien species, as is the case for all the major food crops and husbanded terrestrial animals. However, voluntary and or accidental introduction of exotic aquatic species (alien species) is known to negatively impact local biodiversity. In this relatively young food production industry, mitigating the dependence on alien species, and thereby minimizing potential negative impacts on biodiversity, is an imperative for a sustainable future. In this context an attempt is made in this synthesis to understand such phenomena, especially with reference to Asian inland finfish, the mainstay of global aquaculture production. It is pointed out that there is potential for aquaculture, which is becoming an increasingly important food production process, not to follow the past path of terrestrial food crops and husbanded animals in regard to their negative influences on biodiversity.

INTRODUCTION

Aquatic foods are becoming increasingly important in the human diet. Finfish in particular provide an affordable source of animal protein to rural poor in developing countries (1), and, in the western world, the renowned health benefits of eating fish (2–4) are contributing to its increasing demand. The traditional supplies of aquatic food products were predominantly from marine capture fisheries, which over the last decade or more have begun to decline, or plateau at best (5–8). Aquaculture, since the 1980s, on the other hand, has often been mooted as a possible means of narrowing the gap between supply and demand for aquatic food.

Aquaculture, which in 2004 accounted for 43% of all aquatic food consumed, is considered the fastest growing global primary industry (9). Aquaculture production grew at an average annual rate of 8.9% from 1950 to 2004. Asia dominates aquaculture production, the bulk of which is rural, contributing over 90% to global production (and about 80% of value). Moreover, nations without any such previous tradition are now becoming significant producers of cultured aquatic commodities (10, 11).

The increasing emphasis on aquaculture as a means of reducing the gap between the supply and demand for aquatic food has been questioned on environmental grounds, in particular its dependence on fishmeal supplies for aquatic feeds (12, 13), which in turn depend on approximately 25% of the dwindling marine capture fishery. However, in this regard, it is alleged that aquaculture, which currently accounts for only about 30% usage of global fish meal supplies (14), has been unfairly singled out by critics of the industry (15), and in general the usage of fish meal and raw forage fish (trash fish) in non–human food production sectors has not been taken into account in past analyses (16).

A second concern on aquaculture activities has been expressed with regard to its potential impact on biodiversity. Although the influence of aquaculture on biodiversity has been considered in general terms (17, 18), its increasing dependence on alien species (19) is thought to pose a major threat to biodiversity, an aspect that has not been dealt with in detail previously. The situation is further exacerbated in view of the very limited amount of naturally available habitable freshwater resources (0.01% of the Earth's water resources) on the planet (20, 21), which happen to harbor an estimated 25% of global vertebrate diversity (22). The biodiversity of freshwater ecosystems is reputed to be declining at far greater rates than even the most affected terrestrial ecosystems (23), and consequently it is imperative that all future aquaculture developments pay heed to this aspect, as a priority.

In the present paper, we focus on the possible negative impacts of alien species on biodiversity with respect to cultured freshwater finfish, the mainstay of global aquaculture production. Particular attention is paid to the Asian aquaculture sector, which currently accounts for over 90% of global production. Eventually, attempts are made to draw parallels with what has occurred, over the years, in other food production sectors and suggest mitigating measures.

Alien Species in Aquaculture

An alien species is defined as one that has been translocated, accidentally or deliberately, beyond its natural distribution range. In the present study, the natural distribution of the species in question was determined with reference to the database "Fishbase" (24) and also checked against the Catalogue of Fishes of the California Academy of Sciences, also commonly referred to as the Eschmeyer Catalogue.

It is known that the great bulk of global fish introductions/translocations have been carried out for aquaculture purposes (25, 26), and such introductions are a common occurrence even now (27, 28). Regrettably, there appears to be very little adherence to codes of practices (29) in affecting translocations, even though most nations are signatories to such codes (30). Needless to say, fresh concerns on the issue of translocations are being addressed widely, such as, for example, the European Union Council Regulation of 11 June 2007 (31).

Often when attention is paid to translocations it is restricted to intercontinental introductions rather than intracontinental and between watersheds introductions, which can have an equally negative impact, particularly on biodiversity. On the other hand, even in nations where legislation exists to prevent minimizing the spread of alien species, effective implementation of such laws can often be hampered by other factors (27).

Over 250 aquatic species are cultured globally. Annual production of cultured aquatic species, however, exceeds 10 000 t only for about 115 animal species, of which 67 are finfish (32). Importantly, for 6 of the top ranked 22 freshwater finfish species (produced in excess of 100 000 t per year) or species groups cultured globally, 20% or more of the

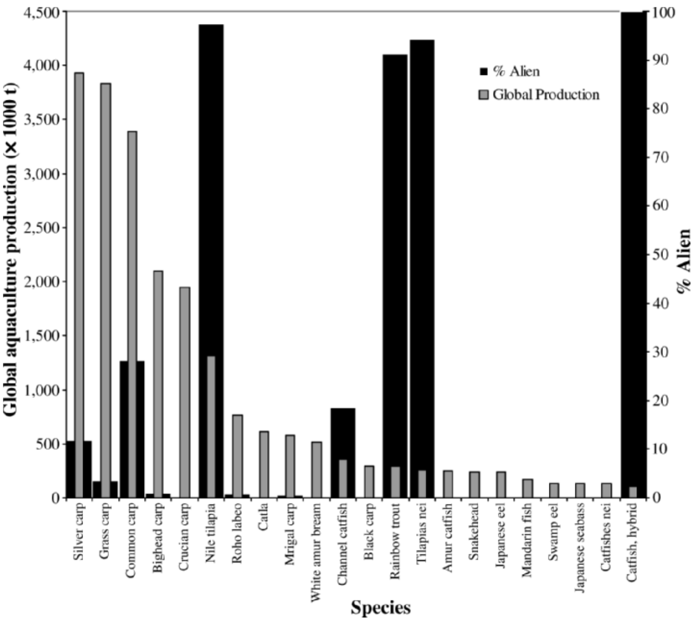

Figure 1. Species and species groups of cultured freshwater finfish (light bars) of which the global production exceeded 100 000 t in 2004, and the proportion (%) of each of these that are produced outside their natural range of distribution (dark bars).

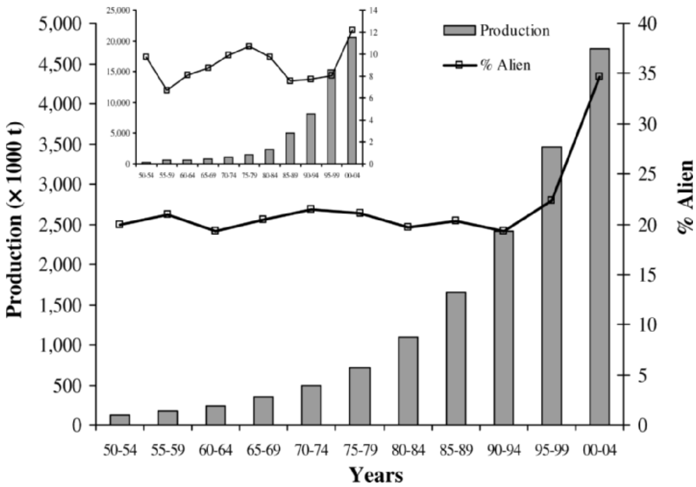

Figure 2. Mean yearly production of cultured freshwater finfish in Asian nations, excluding China, and the percentage contribution of the alien production to total Asian freshwater finfish culture (% alien). The production trend including PR China is given in the inset (modified after De Silva, Sim, and Turchinni [19]).

production occurred outside their natural range of distribution (Fig. 1). Although not clearly seen from Figure 1, it should be noted that, from a geographical viewpoint, the most widespread alien finfish species used in aquaculture is rainbow trout.

The mean yearly cultured alien freshwater finfish production from 2000 to 2004 amounted to 3.6 million t, or 16% of the global finfish aquaculture production (32). It has been shown that in Asia, the epicenter of aquaculture production and development, in the last 5 y, alien finfish species accounted for 12.2% of total cultured finfish production, and the proportion was as much as 35% when PR China is not considered (Fig. 2) (19). Moreover, it is evident that the dependence on alien freshwater finfish in aquaculture has been steadily increasing over the years. Entire national aquaculture industries have been built upon alien species, particularly in nations that have taken up aquaculture in recent times, as in the case of the freshwater crayfish and salmonid culture in Ecuador and Chile, respectively (10, 11).

Impacts of Alien Species on Biodiversity

Fish introduction, which results in alien (i.e., exotic) species, is considered to be one of the biggest threats to finfish biodiversity (33, 34). In the present contribution, we do not loosely use the term “invasive” to describe any introduction of nonindigenous species or introduced species that spread rapidly in the new region. This is because there is no strong link between invasion and its impact as suggested by Ricciardi and Cohen (35). Alien species can impact biodiversity, directly or indirectly (Fig. 3), and these impacts can be immediate or long term. The potential impact of alien species on biodiversity cannot be ignored easily because high-impact invaders are more likely to belong to genera not already present in the system (36). Most watersheds within continents cover vast areas, impacts of alien species can spread far and wide, and translocated organisms can even become invasive. Currently, aquatic habitats, particularly in the developing world, are under serious threat from anthropogenic activities such as dam building (37) and other developments in the watersheds (38). Most of the cultured alien species are somewhat noncatholic in their habitat requirements, and habitat deterioration often facilitates the invasiveness of alien species, a good example being the spread of tilapias throughout Asia (39).

Examples of negative influences on biodiversity arising from fish introductions are recorded from many parts of the globe, the most controversial one being that of the Nile perch (*Lates niloticus*) into Lake Victoria, Africa (40). In Asia, one of the worst documented negative effects on fish biodiversity has resulted from the translocation of grass carp, *Ctenopharyngodon idella* in Donghu Lake, Wuhan, China. Grass carp introduction resulted in the decimation of submerged macrophytes, and the consequent ecological changes brought about an upsurge of bighead (*Aristichthys nobilis*) and silver carps (*Hypophthalmichthys molitrix*) and simultaneously the disappearance of most of the 60 fish species native to the lake (41). Perhaps the impacts on biodiversity of salmonids, in particular species of trout, one of the most extensively moved species across continents into temperate climates, have received less attention than desired. This apparent negligence could be attributed to the dominant role of such species as recreational/sport fishery objects, which brings about significant social and economic benefits, but not necessarily environmental benefits. Admittedly, some negative impacts of these translocations are beginning to be documented

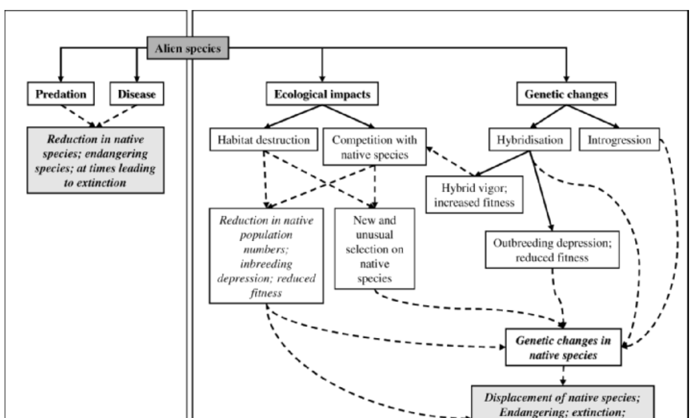

Figure 3. Schematic diagram of potential direct and indirect effects on biodiversity impacts from alien species.

Table 1. Number of instances of introduction of 17 species of tilapinii fishes and their ecological and socioeconomic impacts. Ad, adverse effects; Bf, beneficial effects; Un, unknown. Where relevant, the percentages are given in parentheses (Source: FAO [69]).

		Ecological effects			Socioeconomic effects		
Species	No.	Ad	Bf	Un	Ad	Bf	Un
Oreochromis aureus	13	0	1	42	0	7	36
Oreochromis macrochir	21	0	0	21	0	1	20
Oreochromis mossambicus	91	7	5	79	4	19	68
Oreochromis niloticus	79	2	6	71	0	28	51
Oreochromis urolepis honorum	22	0	0	22	0	1	21
Tilapia rendalli	32	2	0	30	2	2	28
Tilapia zilli	30	2	0	28	0	1	29
Other *Tilapinii* spp.	31	4	1	26	0	0	31
Total	349	17 (4.9)	13 (3.7)	319 (91.4)	6 (1.7)	59 (16.9)	284 (81.4)

(42, 43), but a global synthesis of these translocations is urgently warranted.

Alien species, both aquatic and terrestrial, have been responsible for the introduction of new pathogens and diseases world over (44). From an aquaculture view point, probably the worst occurred with the introduction of the North American crayfish (*Pacifastacus leniusculus*) into Europe, which is thought to have been responsible for the near decimation of the European crayfish (*Astacus astacus*) (45, 46). Evidently *P. leniusculus* brought with it the fungus *Aphanomyces astaci* (47, 48), although it has also been suggested that this fungus may have been inadvertently introduced through ballast water (49). Fortunately, to date, similar large-scale decimation of finfish species through the introduction of pathogens associated with an alien finfish species is unknown, although there have been many pathogen transfers associated with alien species in aquaculture.

Changes in genetic diversity of natural populations resulting from molecular genetically enhanced aquaculture escapees, estimated at about three million per year and considered to be a danger to ecosystems (50), and also from the use of hatchery bred stocks for stock enhancement purposes, are becoming increasingly evident. Loss of diversity in a number of natural populations of *Oncorhynchus* and *Salmo* species has been reported in watersheds in the western United States (51, 52) and in the Atlantic watersheds in Europe (53), respectively. For example, rainbow trout (*Oncorhynchus mykiss*) hybridize easily and extensively with threatened Apache trout (*Oncorhynchus apache*) and endangered Gila trout (*Oncorhynchus gilae*). It has been reported that currently 65% of Apache trout have rainbow trout alleles and, at least in one instance, one whole native Apache trout population has been completely replaced by rainbow trout. Similarly, in Asia, introgression of African catfish (*Clarias gariepinus*) genes into the native walking catfish *Clarias macrocephalus* has been reported in wild (54) and two broodstock populations in Thailand (55). Consequently, it has been suggested that the indigenous walking catfish is being increasingly threatened as a result of massive backcrossing with hybrid catfish, which is the preferred catfish of Thai catfish farmers (55). A comparable problem has been found in Bangladesh through the use of hybrid *Clarias batrachus* × *C. gariepinus* for aquaculture (56).

Modern Farming

Production of the vast majority of food crops and a significant proportion of husbanded terrestrial animals occurs in regions beyond the natural distribution range of these species; this type of production is the backbone of modern agriculture (57). However, these introductions mostly took place prior to the last century when environmental concerns that could result from introduced species were of little or no concern, and received scant attention. The detrimental impacts on biodiversity of such introductions, in conjunction with plowing of pristine habitats, damming of rivers, and deforestation, among others, carried out for purposes of food production are well documented (38, 57–60). It is in the above context that modern agriculture is generally acknowledged to be the primary destructive force of biodiversity (60). The expansion of global croplands, pastures, plantations, and urban areas, in conjunction with large increases in energy, water, and fertilizer usage, have brought forth the challenge of managing the tradeoffs between meeting immediate human needs and maintaining the capacity of the planet to sustain these needs in the long term (61). On the other hand, some believe that modern agriculture, with its current practices, may still hold the key to saving the richness of life on earth (57).

Mitigating Impacts of Cultured Alien Species on Biodiversity

Aquaculture, though a very old tradition, is essentially an industry of the last quarter of the twentieth century. Strategies are available that could be adopted to minimize its impacts on biodiversity. If not, it will be a paradox that a contemporary food industry follows the same path as those before, and the impending consequences are difficult, if not impossible, to assess. One of the most pragmatic approaches for the still growing aquaculture industry would be to take steps to reduce its dependence on alien species, one single factor that is considered by many to impact biodiversity to the highest extent (33, 34, 59). Accordingly, there is a need to minimize both inter- and intracontinental translocations, as well as translocations between watersheds. Moreover, there is a need for a greater emphasis on applying accepted codes of practices (30, 62) when such translocations are planned and executed. This is of particular importance, since there is evidence that ecological disasters result from deliberate or accidental introduction of alien invasive species (27, 40) coupled with habitat deterioration through anthropogenic activities (63).

Apart from minimizing any fresh introductions, all future strategies that are, or will be, adopted to sustain biodiversity should, however, take into account that such steps do not overly influence the increasing role of aquaculture as a food production source. Moreover, in addressing the issue, the socioeconomic conditions of the practitioners need to be carefully considered so that their well being is not adversely affected. Aquaculture practitioners, particularly in Asia, tend to be mostly rural, small-scale/family farmers depending on aquaculture as their sole livelihood and, having a relatively weak voice within the global political/decision making scenarios, need to be backed up and not hampered in their activities.

One of the most acceptable and easily achievable strategies would be to lay more emphasis on the culture of indigenous species. Indeed, the backbone of global aquaculture, contributing nearly 55.5% to global cultured finfish production, is represented by common, Chinese and Indian major carp farming in rural Asian aquaculture, and it may well be an accident of history. The artificial propagation and larval rearing techniques of these species were developed at the time when aquaculture began to be popularized as a strategy for reducing the widening gap between supply and demand for aquatic food. There is no reason to believe that some of the cultured alien species could not be replaced with indigenous species, hand in hand with technical and relevant policy developments: a view that is gaining increasing momentum (64, 65). However, the trends in this regard are not consistent. For example, it has been demonstrated that in some Asian nations the emphasis on indigenous species is increasing (e.g., Indonesia, Malaysia, and in recent years Thailand) but the reverse (e.g., India and Bangladesh) is seen in others (19), and similar contrasting trends have been reported in European inland aquaculture (28). It is well known that some of the potential candidate indigenous species are often preferred over alien species by the respective communities, and therefore a shift to indigenous species is unlikely to encounter significant resistance from consumers. Furthermore, already significant losses in performance in some alien species resulting primarily from inbreeding have been reported (58). As a first step, rather than replenishing such alien brood stocks, lock, stock, and barrel, with fresh germplasm obtained from their natural range of distribution, attempts need to be made to develop viable and profitable culture techniques for suitably selected indigenous species (66). These can then replace the poorly performing alien species.

There are examples of rather recent finfish aquaculture developments, based on indigenous species, particularly in Asia, indicative of the available potential to gradually reduce the dependence on alien species, without loss in overall production and socioeconomic benefits. A case in point in this regard is the pangasid fish culture (*Pangasianodon hypophthalmus,* popularly known as tra catfish) in the Mekong Delta, with a production of 825 000 t in 2006 (67).

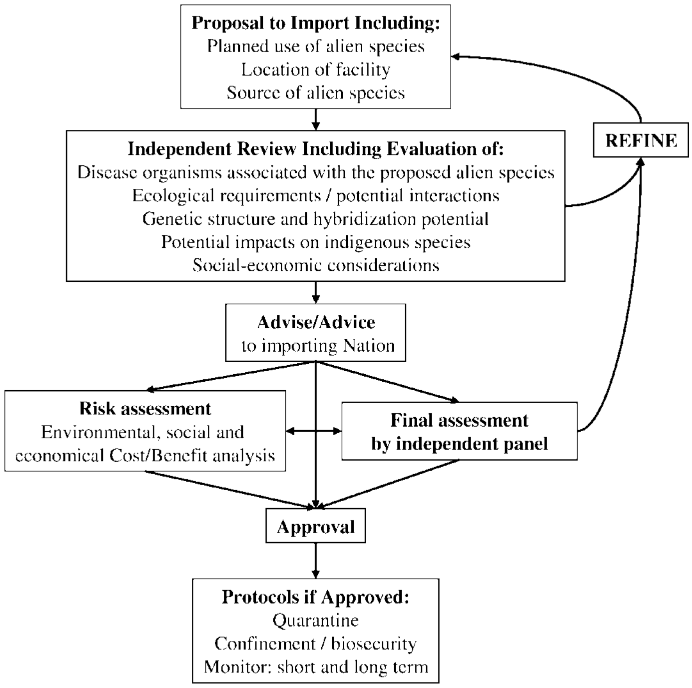

Figure 4. Main elements of a code of practice for the introduction of aquatic species (modified after Bartley and Minchin [63]).

A Dilemma

Our argument is in no way based on the view that the existing situation is completely unacceptable and needs a total overhaul. Aquaculture itself is an alteration of the natural system, but it is one of the few alternatives available to assure food security in the form of an animal protein supply for ever increasing human populations, especially rural populations in developing countries. It is also a fact that natural geographical distribution of freshwater fish species limits species availability for aquaculture. Fish species suitable for aquaculture indeed are required to possess certain characteristics such as fast growth rate and good food conversion efficiency, among others. In countries with a highly diverse freshwater fish fauna, finding suitable candidates for aquaculture possessing these characteristics is not impossible. However, in small islands where fish biodiversity is generally low (68), species suitable for aquaculture are rare in the indigenous fish fauna. Consequently, such countries are compelled to depend on alien fish species, if aquaculture is to be chosen as a means for food security. A case in point in this regard is the alien tilapias, which are known to play a major role in aquaculture systems in China, Indonesia, the Philippines, and Sri Lanka, providing a relatively cheap source of animal protein for rural poor, as well as considerable export income (39). According to the database on introductions of aquatic species found in the Food and Agriculture Organization (FAO) of the United Nations fisheries global information system (69), there were 349 instances of introduction of 17 species of tilapias. In most cases, significant problems either ecologically or socioeconomically were not observed, and in fact in nearly 17% of the cases there were socioeconomic benefits, as opposed to 1.7% of cases with adverse socioeconomic impacts (Table 1). The adverse effects and benefits are undoubtedly derived from an anthropocentric viewpoint, but the benefits that mankind have received from the introduction of these exotic species cannot be negated. This is also a paradox with regard to food production when the issue is viewed from the context of rural development. As can be seen from Figure 4, introduction of exotic species can be mitigated if a proper mechanism is derived and implemented.

There is potential for aquaculture, which is becoming an increasingly important food production process, not to follow the past path of terrestrial food crops and husbanded animals in regard to their negative influences on biodiversity (70). However, this will need a global approach and a profound understanding. In this regard, the increasingly stringent legislation of major cultured aquatic food importing nations, demanding strict adherence to codes of practices that minimize negative influences on biodiversity and assurance of maintenance of environmental integrity, is promising. It will facilitate a gradual reduction on the dependence of alien species in aquaculture, the primary factor that is thought to impact biodiversity. Of course this does not negate the judicious use of alien species in aquaculture development, if and where needed.

References and Notes

1. Delgado, C.L., Wada, N., Rosegrant, M.W., Meijer, S. and Ahmed, M. 2003. *Fish to 2020. Supply and Demand in Changing Global Market*. International Food Policy Research Institute, Washington, DC, 226 pp.
2. Simopoulos, A.P, Leaf, A. and Salem, N. 1999. Essentiality of and recommended dietary intakes for omega-6 and omega-3 fatty acids. *Ann. Nutr. Metab. 43*, 127–130.
3. Connor, W.E. 2000. Importance of *n*-3 fatty acids in health and disease. *Am. J. Clin. Nutr. 71*, 171S–175S.
4. Seierstad, S.L., Seljeflot, I., Johansen, O., Hansen, R., Haugen, M., Rosenlund, G., Frøyland, L. and Arnsesn, H. 2005. Dietary intake of differently fed salmon; the influence on markers of human atherosclerosis. *Eur. J. Clin. Invest. 35*, 52–59.
5. Botsford, L.W., Castilla, C.J. and Peterson, C.H. 1997. The management of fisheries and marine ecosystems. *Science 277*, 509–514.
6. Watson, R. and Pauly, D. 2001. Systematic distortions in world fisheries catch trends. *Nature 414*, 534–536.
7. Pauly, D., Alder, J., Bennett, E., Christensen, V., Tyedmers, P. and Watson, R. 2003. The future of fisheries. *Science 302*, 1359–1361.
8. Zeller, D. and Pauly, D. 2005. Good news, bad news: global fisheries discards are declining but so are the total catches. *Fish Fish. 6*, 156–159.

9. Food and Agriculture Organization of the United Nations (FAO) 2006. *The State of World Fisheries and Aquaculture*. Fisheries and Aquaculture Department, Rome, Italy, 162 pp.
10. Romero, X. 1997. Production of redclaw crayfish in Ecuador. *World Aquac. 28*, (2), 5–10.
11. Gajardo, G. and Laikre, L. 2003. Chilean aquaculture boom is based on exotic salmon resources: a conservation paradox. *Conserv. Biol. 17*, 1173–1174.
12. Naylor, R.L., Goldburg, R.J., Mooney, H., Beveridge, M., Clay, J., Folke, C., Kautsky, N., Lubchenco, J., et al. 1998. Nature's subsidies to shrimp and salmon farming. *Science 282*, 883–884.
13. Naylor, R.L., Goldburg, R.J., Primavera, J., Kautsky, N., Beveridge, M., Clay, J., Folke, C., Lubchenco, J., et al. 2000. Effect of aquaculture on world fish supplies. *Nature 405*, 1097–1024.
14. Tacon, A.G.J. 2004. Use of fish meal and fish oil in aquaculture: a global perspective. *Aquat. Resour. Cult. Dev. 1*, 3–14.
15. Hardy, R.W. 2001. Urban legends and fish nutrition, Part 2. *Aquac. Mag. 27*, (2), 57–60.
16. De Silva, S.S., Sim, S.Y. and Turchinni, G. Review on usage of fish, directly and indirectly, as feed ingredients and feeds in Asian-Pacific aquaculture. FAO Fisheries Technical Paper. (In press).
17. Beveridge, M.C.M., Ross, L.G. and Kelly, L.A. 1994. Aquaculture and biodiversity. *Ambio 23*, 497–504.
18. Beardmore, J.A., Mair, G.C. and Lewis, R.I. 1997. Biodiversity in aquatic systems in relation to aquaculture. *Aquac. Res. 28*, 829–839.
19. De Silva, S.S., Nguyen, T.T.T., Abery, N.W. and Amarasinghe, U.S. 2006. An evaluation of the role and impact of alien finfish in Asian inland aquaculture. *Aquacult. Res. 37*, 1–17.
20. Shiklomanov, I.A. 1993. World freshwater resources. In: *Water in Crisis: A Guide to the World's Fresh Water Resources*. Gleick, P.H. (ed). Oxford University Press, New York, pp. 13–24.
21. Shiklomanov, I.A. 1998. *Archive of World Water Resources and World Water Use*. Global Water Data Files: State Hydrological Institute. Data archive on CD-ROM from State Hydrological Institute, St. Petersburg, Russia.
22. Groombridge, B. (ed). 1992. *Global Biodiversity: Status of the Earth's Living Resources*. Chapman and Hall, London, 285 pp.
23. Ricciardi, A. and Rasmussen, J.B. 1999. Extinction rates of North American freshwater fauna. *Conserv. Biol. 13*, 1220–1222.
24. Froese, R. and Pauly, D. (eds). 2007. FishBase. (http://www.fishbase.org).
25. Welcomme, R.L. 1988. International introductions of inland aquatic species. *FAO Fisheries Technical Paper 213*, 120 pp.
26. De Silva, S.S. (ed). 1989. *Exotic Organisms in Asia*. Asian Fisheries Society Special Publication 3, Manila, Philippines, 154 pp.
27. Naylor, R.L., Williams, S.L. and Strong, D.R. 2001. Aquaculture—a gateway for exotic species. *Science 294*, 1655–1666.
28. Turchini, G.M. and De Silva, S.S. 2007. Bio-economical and ethical impacts of alien finfish culture in European inland waters. *Aquac. Int*. (In press). (doi: 10.1007/s10499-007-9141-y)
29. International Council for the Exploration of the Sea (ICES) 1995. *ICES Code of Practices on the Introduction and Transfers of Marine Organisms*. International Council for Exploration of the Sea, Copenhagen, Denmark, 5 pp.
30. Bartley, D.M. and Casal, C.V. 1998. Impacts of introductions on the conservation and sustainable use of aquatic biodiversity. *FAO Aquac. Newsl. 20*, 15–19.
31. European Union Council Regulation 708/2007. 2007. EU Council Regulation (EC) 708/2007 of 11 June 2007 concerning use of alien and locally absent species in aquaculture. *Off. J. Eur. Union L168,* 1–17.
32. FAO. 2006. *Fishstat plus: universal software for fishery statistical time series;* Version 2.3. FAO, Data and Statistics Unit of the Fisheries and Aquaculture Department, Rome, Italy.
33. Moyle, P.B. and Leidy, R.A. 1992. Loss of biodiversity in aquatic ecosystems; evidence from fish faunas. In: *Conservation Biology: The Theory and Practice of Nature Conservation*. Fielder, P.L. and Jain, S.K. (eds). Chapman and Hall, London, pp. 129–161.
34. National Research Council. 2001. *Understanding Marine Biodiversity: A Research Agenda for the Nation*. National Academy Press, Washington, DC, 121 pp.
35. Ricciardi, A. and Cohen, J. 2007. The invasiveness of an introduced species does not predict its impact. *Biol. Invasions 9*, 309–315.
36. Ricciardi, A. and Atkinson, S.K. 2004. Distinctiveness magnifies the impact of biological invaders in aquatic ecosystems. *Ecol. Lett. 7*, 781–784.
37. McCully, P. (ed). 1995. *Silenced Rivers. The Ecology and Politics of Large Dams*. Zed Books, London, 352 pp.
38. Sodhi, N.S., Koh, L.P., Brook, B.W. and Ng, P.K.L. 2004. Southeast Asian biodiversity: an impending disaster. *Trends Ecol. Environ. 19*, 654–660.
39. De Silva, S.S., Subasinghe, R.P., Bartley, D.M. and Lowther, A. 2004. *Tilapias as Alien Aquatics in the Asia-Pacific: A Review. FAO Fisheries Technical Paper 453*. FAO, Rome, 65 pp.
40. Barel, C.D.N., Dorit, R., Greenwood, P.H., Fryer, G., Hughes, N., Jackson, P.B.N., Kawanabe, H., Lowe-McConnell, R.H., et al. 1985. Destruction of fisheries in Africa's lakes. *Nature 315*, 19–20.
41. Chen, H.D. 1989. Impact of aquaculture on the ecosystem of Donghu Lake, Wuhan. *Acta Hydrobiol. Sin. 13*, 359–368. (In Chinese).
42. McDowall, R.M. 2003. Impacts of introduced salmonids on native galaxiids in New Zealand upland streams: a new look at an old problem. *Trans. Am. Fish. Soc. 132*, 229–238.
43. Blanchet, S., Loot, G., Grenouillet, G. and Brosse, S. 2007. Competitive interactions between native and exotic salmonids: a combined field and laboratory demonstration. *Ecol. Freshw. Fish 16*, 133–143.
44. Daszak, P., Cunningham, A.A. and Hyatt, A.D. 2001. Anthropogenic environmental change and emergence of infectious diseases in wildlife. *Acta Trop. 78*, 103–116.
45. Reynolds, J.D. 1988. Crayfish extinction and crayfish plague in Central Ireland. *Biol. Conserv. 45*, 279–285.
46. Bäck, S.B. 1995. Replacement of the native crayfish *Astacus astacus* by the introduced species *Pacifastacus leniusculus* in a Swedish lake: possible causes and mechanisms. *Freshw. Biol. 33*, 291–298.
47. Alderman, D.J., Polglase, J.L., Frayling, M. and Hogger, J. 1984. Crayfish plague in Britain. *J. Fish Dis. 7*, 401–405.
48. Edgerton, B.E., Henttonen, P., Jussila, J., Mannonen, A., Paasonen, P., Taugbøl, T., Edsman, L. and Souty-Grosset, C. 2004. Understanding the cause of disease in European freshwater crayfish. *Conserv. Biol. 18*, 1466–1474.
49. Vogt, G. 1999. Diseases of European freshwater crayfish with particular emphasis on interspeceific transmission of pathogens. In: *Crayfish in Europe as Alien Species, How to Make the Best of a Bad Situation*. Gherardi, F. and Holdich, D.M. (eds). A.A. Balkema, Amsterdam, pp. 87–103.
50. Anonymous 2007. Escapes from aquaculture are a danger to ecosystems. *Eurofish Mag. 1*, 90–93.
51. Dowling, T.E. and Childs, M.R. 1992. Impact of hybridisation on a threatened trout of the Southwestern United States. *Conserv. Biol. 6*, 355–364.
52. Leary, R.F., Allendorf, F.W. and Forbes, S.H. 1993. Conservation genetics of bull trout in the Columbia and Klamath River drainages. *Conserv. Biol. 7*, 856–865.
53. Cagigas, M.E., Vãzquez, E., Blanco, G. and Sãnchez, J.A. 1999. Genetic effects of introduced hatchery stocks on indigenous brown trout (*Salmo trutta* L.) populations in Spain. *Ecol. Freshw. Fish 8*, 141–150.
54. Senanan, W., Kapuscinski, A.R., Na-Nakorn, U. and Miller, L. 2004. Genetic impacts of hybrid catfish farming (*Clarias macrocephalus* × *C. gariepinus*) on native catfish populations in central Thailand. *Aquaculture 235*, 167–184.
55. Na-Nakorn, U., Kamonrat, W. and Ngamsiri, T. 2004. Genetic diversity of walking catfish, *Clarias macrocephalus,* in Thailand and evidence of genetic introgression from introduced farmed *C. gariepinus*. *Aquaculture 240*, 145–163.
56. Rahman, M.A., Bhadra, A., Begum, N., Islam, M.S. and Hussain, M.F. 1995. Production of hybrid vigour cross breeding between *Clarias batrachus* Lin. & *Clarias gariepinus* Bur. *Aquaculture 138*, 125–130.
57. Lockwood, J.A. 1999. Agriculture and biodiversity: finding our place in the world. *Agric. Hum. Values 16*, 365–379.
58. Wilson, E.O. (ed). 1992. *The Diversity of Life*. Norton, New York, 424 pp.
59. Cox, G.C. 1999. *Alien Species in North America and Hawaii. Impacts on Natural Ecosystems*. Island Press, Washington, DC, 400 pp.
60. Pimentel, D. (ed). 2002. *Biological Invasions. Economic, Environmental Costs of Alien Plant, Animal and Microbe Species*. CRC Press, Boca Raton, 336 pp.
61. Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, S., Coe, M.T., et al. 2005. Global consequences of land use. *Science 309*, 570–575.
62. Bartley, D.M. and Minchin, D. 1996. Precautionary Approach to the Introduction and Transfer of Aquatic Species. FAO Fisheries Technical Paper 350, pp. 159–189.
63. Odada, E.O., Olago, D.O., Kulindwa, K., Ntiba, M. and Wandiga, S. 2004. Mitigation of environmental problems in Lake Victoria, East Africa: causal chain and policy options analyses. *Ambio 33*, 13–23.
64. Pérez, J.E., Alfonsi, C., Nirchio, M., Muñoz, C. and Gómez, J.A. 2003. The introduction of exotic species in aquaculture: a solution or part of the problem? *Interciencia 28*, 234–238.
65. Welcomme, R.L. and Chavalit, W. 2003. *The Impacts of Introductions and Stocking of Exotic Species in the Mekong Basin and Policies for Their Control. MRC Technical Report No 9*. Mekong River Commission, Vientiane, Lao PDR, 35 pp.
66. Nguyen, T.T.T., Ingram, B., Sungan, S., Gooley, G., Sim, S.Y., Tinggi, D. and De Silva, S.S. 2006. Mitochondrial DNA diversity of broodstocks of two indigenous fish species, *Tor tambroides* and *T. douronensis* (Cyprinidae) cultured in Sarawak, Malaysia. *Aquaculture 253*, 259–269.
67. Nguyen, H.V. 2007. Vietnam's catfish and marine shrimp production: an example of growth and sustainability. *Aquac. Asia-Pacific 3*, (4), 36–39.
68. Penman, D.J., Mair, G.C., McAndrew, B.J., Hussain, M.G., Basavaraju, Y. and Tuan, P.H. 2002. Genetic management of non-indigenous carps of low-input aquaculture systems in Asia. *Aquac. News 28,* 19–20.
69. FAO. 2007. *Database on Introductions of Aquatic Species (DIAS)*. FAO Data and Statistics Unit of the Fisheries and Aquaculture Department, Rome, Italy.
70. Waples, R.S. 1991. Genetic interactions between hatchery and wild salmonids: lessons from the Pacific Northwest. *Can. J. Fish. Aquat. Sci. 48*, 124–133.

71. Giovanni M. Turchini's contribution to this study was made while holding an APD Discovery, postdoctoral fellowship from the Australian Research Council (ARC) for the project DP0772271, whose support is gratefully acknowledged.
72. First submitted 26 December 2006. Accepted for publication 6 June 2007.

Sena S. De Silva is the Director General of Network of Aquaculture Centers in Asia-Pacific and also an Honorary Professor, School of Life & Environmental Sciences, Deakin University, Victoria, Australia. His address: PO Box 1040, Kasetsart Post Office, Gangkok 10903, Thailand.
E-mail: sena.desilva@enaca.org

Thuy T. T. Nguyen is the Coordinator of the Genetics and Biodiversity Work Program of the Network of Aquaculture Centers in Asia-Pacific. Her address: PO Box 1040, Kasetsart Post Office, Bangkok 10903, Thailand.
E-mail: thuy.nguyen@enaca.org

Giovanni M. Turchini is a Lecturer of the School of Life and Environment Sciences, Deakin University. His address: School of Life and Environment Sciences, Deakin University, Warrnambool, Victoria 3280, Australia.
E-mail: giovanni.turchini@deakin.edu.au

Upali S. Amarasinghe is a Professor in the Department of Zoology, University of Kelaniya. His address: Department of Zoology, University of Kelaniya, Kelaniya, Sri Lanka.
E-mail: zoousa@kln.ac.lk

Nigel W. Abery is a Researcher in the Department of Primary Industries, Fisheries Victoria. His address: Department of Primary Industries, Fisheries Victoria, Snobs Creek, Victoria, Australia.
E-mail: nigel.abery@dpi.vic.gov.au