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Review Article

The Effects of Species Interactions Resulting from Aquaculture Operations*

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Abstract

Aquaculture production is increasing rapidly as modern techniques are applied to an expanding range of species. One particularly adverse consequence of aquaculture is the impact of interactions between the organism under culture, which is often both exotic and invasive by nature, and the indigenous biota of the surrounding environment. Species interactions due to aquaculture activities may result from the attraction of local biota to culture facilities, or the escape of cultured organisms, their diseases or parasites into the environment. The effects of species interactions can be classified as: disturbance of the local aquatic environment, disturbance of the surrounding biotic community, genetic degradation of indigenous stock, and the introduction of diseases and parasites. Drawing on the aquaculture experiences of developed and developing countries, this paper reviews the various types of species interactions and their effects on the local environment. These issues are discussed in terms of direct ecological effects and the human perspectives (management, government, local community) pertaining to the various culture systems. Examples are drawn from aquaculture activities in a range of habitats (freshwater, brackish water, marine), culture systems (intensive, semi-intensive, extensive), and culture facilities (cages, pens, ponds). Approaches to the management of invasive species are then outlined.

Introduction

With the declining returns of world fisheries, aquaculture is looked upon as a way to provide increasing quantities of aquatic product in the future (Beveridge 1987). Aquaculture production is increasing rapidly as modern techniques are applied to an expanding range of species (Pullin 1993a). Furthermore, subsistence and small-scale aquaculture is often the only source of animal protein for people in developing countries, as well as being a potential method for improving the standard of living of rural-based communities (Cvasas 1993; Pullin 1993b). Thus aquaculture is important both as a means of providing food and for improving the quality of life.

Aquaculture activities and products from culture facilities can affect the environment in many ways. The principal adverse impacts include the

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destruction and fragmentation of natural habitats, changes in soil, water and landscape quality, changes in the abundance of species, impoverishment of genetic and biological diversity, and disturbance of ecosystem processes (GESAMP 1991; Weston 1991). The magnitude of such impacts varies with the nature and location of the culture system (extensive, semi-intensive, and intensive aquaculture in marine, brackish, and inland areas), the methods of husbandry used and the species under cultivation.

Irrespective of the type of aquaculture system or management strategies employed, escapes into the wild are virtually impossible to prevent (Beveridge and Phillips 1993). Therefore, all forms of aquaculture have one impact in common - the adverse ecological consequences to the indigenous biota and surrounding environment which may arise as the result of the escape of the organisms under culture (Pullin 1989; Chua 1993; Pullin 1993b).

There is now a general appreciation that species interactions, especially those resulting from the establishment of self-sustaining introduced species or the alteration of indigenous gene pools, are potentially the most damaging environmental consequences of aquaculture (Welcomme 1988; Barg 1992; Pullin, Rosenthal and Maclean 1993). Whereas most of the effects of aquaculture on local habitats and water quality can be managed or minimised by careful selection of sites, effluent control, and good husbandry, the management of an established introduced species is extremely difficult. The effects of the ensuing species interactions may vary from regional to continental in scale and the impacts on indigenous biota are usually irreversible (Weston 1991; Pullin 1993b).

In this paper we review the major types of species interactions, with particular emphasis on the ecological relationships of exotic and indigenous species, and the consequences for aquatic ecosystems. Principles and examples are drawn from inland and coastal aquaculture systems, including intensive, semi-intensive, and extensive production systems using ponds, cages, pens, and so on. Species interactions involving fish, molluscs and crustaceans are reviewed. The fundamental social and economic aspects driving aquaculture activity are also discussed as they relate to the various perspectives about species interactions and their impact on the environment.

The concept of aquaculture used in this paper is that defined by the FAO (1990), and comprises the farming of stock, by intervention in the rearing process to enhance production, under individual or corporate ownership. This paper is therefore not explicitly concerned with species which are introduced to create or enhance sport and harvest fisheries. Nevertheless, we stress that the environmental problems presented are relevant to the management of all introduced species irrespective of the motives for their introduction. In any case, the problems of exotic and translocated species in general are thoroughly documented elsewhere (e.g. Courtenay and Stauffer 1984; Bruton and van As 1986; Turner 1988; Welcomme 1988; De Silva 1989; Pollard 1990; Billington and Hebert 1991; Crowl, Townsend and McIntosh 1992).

An exotic species is defined as one that is not native to the country under discussion, while an indigenous species is one which is native to that country. The term 'introduced species' 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. An established species is one which has formed a self-sustaining population, and species described as invasive have demonstrated the ability to establish themselves in natural waters.

Species Introductions for Aquaculture Purposes

In aquaculture, introductions of exotic species and translocations of indigenous species beyond their natural range are expressly intended to add entirely new elements (species or cultivars) to the production system. Aquaculture, especially intensive aquaculture, is a high risk enterprise and every advantage is taken of opportunities to enhance the productivity of stocks, the quality of the product, and profits. Species with a reputation for excellent performance under cultivation are the most likely choices for introduction to other areas, where building on past experience and available technologies can give a competitive edge and quick returns. Similarly, in the case of low-input aquaculture, species which offer the promise of a reliable source of protein, and which are cheaply available, are sought irrespective of their origins.

In addition, there have been many haphazard introductions of species for pilot aquaculture programs (Welcomme 1988), and a few species deliberately introduced as forage fish in aquaculture systems have escaped to the wild (e.g. species of gudgeon and minnow used in Spanish trout farms; Lobon-Cervia, Elvira and Rincon 1989). In some cases, stocks deliberately introduced for aquaculture have been contaminated with other species which have subsequently escaped and established breeding populations. For example, the Topmouth Gudgeon, *Pseudorasbora parva* Schlegel, a south-east asian cyprinid, was introduced accidentally in the Danube Delta in Romania in the 1960s. As well as achieving a pan-Danubian distribution (Rosecchi, Crivelli and Catsadorakis 1993), this gudgeon has been transferred to Germany, Albania and Lithuania when stocking other species such as European Carp, *Cyprinus carpio* L., and has also been reported in Israel, Italy, France and Greece (Rosecchi *et al.* 1993).

The global extent of species introductions associated with aquaculture has been reviewed comprehensively (Welcomme 1988; Baltz 1991; Munday *et al.* 1992a). In inland waters, introductions for aquaculture purposes appear to far exceed those for any other purpose, including introductions for sport fishing, improvement of wild stocks, for trade in ornamental species, control of undesirable organisms (phytoplankton, plants, disease vectors and nuisance organisms such as mosquitoes) and accidental releases. Welcomme (1988) reported that 98 species of fish have been introduced internationally for aquaculture purposes involving inland waters.

Prior to 1900, the majority of fish species moved outside their normal ranges were salmonids, especially Rainbow Trout, *Oncorhynchus mykiss* (Walbaum), Brown Trout, *Salmo trutta* L. and various species of *Salvelinus*. These species were introduced into temperate areas for cultivation and controlled releases to provide or enhance sport fisheries, and to a much lesser extent for food production. Salmonid introductions reached a peak in the 1890s and more recently, salmonid introductions have largely been limited to anadromous species which are being cultivated in mariculture systems (Welcomme 1988).

The movement of the European Carp, *Cyprinus carpio*, began in Europe in medieval times whilst more recent introductions peaked in the early decades of this century. Tilapias and Chinese carps have become predominant finfish culture species since the Second World War. The most recent wave of introductions has involved crustaceans, including shrimps and prawns for brackish water culture (Welcomme 1988) and crayfish in fresh water (Pillay 1992).

Escapes from Aquaculture

The potential for escape of exotic or translocated species from culture facilities has always been recognised as a risk in aquaculture developments. Escapes into the surrounding environment are inevitable in the long run, and they may involve very large numbers of individuals at any stage of the life history.

The subsequent fate of an introduced species in the new environment is generally unpredictable, since it will depend on dynamic interactions between the genetic, physiological, and biological characteristics of the escapees and the characteristics, dynamics, and history of the receiving environment (Arthington and Mitchell 1986). Many of the characteristics inherent in aquaculture species, such as high reproductive success, wide environmental tolerances, and broad habitat and dietary preferences, correspond to those which typify invasive species (Taylor, Courtenay and McCann 1984; Bruton 1986).

Efforts to identify species likely to become self-sustaining and highly invasive, and to identify environments that are particularly susceptible to invasion (see Li and Moyle 1981; Bruton 1986; Welcomme 1988; Moyle, Li and Barton 1986; Crowl *et al.* 1992), have not really succeeded because of the strong element of chance and our limited understanding of the processes which regulate natural aquatic communities (Baltz 1991).

Another confounding factor is that many of the habitats invaded have been disturbed by human activities, and the significance of such disturbances is not well understood, although often invoked as favouring the establishment of exotic species, at least in freshwater systems (Arthington, Hamlet and Blühdorn 1990; Courtenay 1990; Crowl *et al.* 1992). Due to the paucity of appropriate research, including before-and-after studies, many of the effects attributed to introduced species are not supported by conclusive data (Clugston 1990), and rely on conjecture to separate them from other causal factors such as habitat disturbance, nutrient enrichment and pollution. These factors frequently tend to be associated with aquaculture activities.

Effects of Introduced Species

Beveridge and Phillips (1993) summarise the potential adverse impacts of escaped aquaculture organisms into five categories:

- alterations to the host environment;
- disruption of the host community (principally through predation and competition);
- genetic degradation of local stocks;
- introduction of parasites and diseases;
- socio-economic effects.

Escapees do not have to reproduce in the new environment to cause an impact. The release of very large numbers of individuals which survive to feed and grow will have some effect on local resources and species. For example, typhoons in the Philippines regularly destroy fish pens, and one incident in 1976 released millions of Milkfish, *Chanos chanos* (Forsskal), into Laguna de Bay, boosting local harvest fisheries for weeks after the event (Gabriel 1979). Repeated escapes of exotic species which are regularly imported as larvae and juveniles for grow-out aquaculture are of particular concern, since large populations can persist without natural reproduction (Baltz 1991). A sustained predatory or competitive effect on indigenous species may follow the escape of long-lived species such as anguillids, which may survive for 30 years or more and not reproduce (Baltz 1991).

However, many exotic species escaping to the wild do reproduce and eventually become established and invasive in the new environment. According to Welcomme (1988), about two-thirds of the freshwater species introductions in the tropics have become successfully established. Species that remain a rare component of the aquatic community may have little impact, although this should not necessarily be assumed. If we reject the notion of vacant niches (see Herbold and Moyle 1986; Kikkawa and Anderson 1986), and recognise instead that the introduction of an additional species will result in the redistribution of resources amongst a portion of the community, then at least some change must occur. For rare species, the direction of these changes and their extent and time scales are for the most part obscure, and we have almost no knowledge of their functional effects.

When an established introduced species becomes predominant in the host community, more obvious and measurable changes may take place, ranging from effects on the local aquatic environment to severe disturbance of the community. We regard all of the effects of escaped aquaculture species, and the responses of indigenous biota to aquaculture facilities, as species interactions, and review them individually below.

Species Interactions

Disturbance of the Local Aquatic Environment

There are surprisingly few good examples of environmental degradation due to escaped aquaculture organisms in the sense of direct effects on physical habitat, water quality and biological resources required by other biota. One of the most obvious nuisance species is the European Carp, *C. carpio*, which has been spread to at least 50 countries for cultivation as a food fish, as an ornamental species for ponds and lakes, and to enhance fisheries (Welcomme 1988). Wild populations have become established in many countries within the limits of the species' thermal tolerance, and in some areas introductions of carp have been beneficial. In others, including the United States, Europe, India, South Africa and Australia, the carp has acquired a reputation for causing the degradation of aquatic habitats and water quality (Crivelli 1983; Bruton and van As 1986; Moyle *et al.* 1986; Welcomme 1988; Fletcher, Morison and Hume 1985).

Carp disturb the benthic sediments of freshwater lakes and slow-flowing rivers during feeding, disrupting the production of aquatic invertebrates (Moyle *et al.* 1986) and damaging aquatic macrophytes, especially delicate species (Crivelli 1983; Fletcher *et al.* 1985). The roiling behaviour of carp is believed to increase turbidity levels by re-suspending sediments (but see Fletcher *et al.* 1985), and the fish excrete nutrients which may contribute to accelerated eutrophication (Bruton 1985; Welcomme 1988) and possibly, cyanobacterial outbreaks (P. Gehrke, pers. comm.). In India, eutrophication and the shading out of macrophytes have led to changes in the composition of the indigenous fish fauna, including the disappearance of species in the genus *Schizothorax*, together with their associated fisheries (Jhingran & Sehgal 1978).

Experiences with the European Carp in Australia illustrate the full range of effects ascribed to this species elsewhere. Of the three varieties found in Australia, only one - the hybrid River (or Boolara) strain, an aquaculture escapee - has become invasive, and has undergone extensive range expansion in Australia's largest river system, the Murray-Darling. This has been accompanied, in many areas, by its domination of the fish community, contributing more than 80% of the total fish biomass in regions of the Murray, Lachlan and Murrumbidgee Rivers (P. Gehrke, pers. comm.). In addition to water quality impacts and a possible role in nutrient enrichment and the stimulation of cyanobacterial blooms, it is suspected that habitat modifications caused by carp have contributed to the decline of one endangered species: the Trout Cod, *Maccullochella macquariensis* (Cuvier) and three vulnerable species: the Dwarf Galaxias *Galaxias pusilla* (Mack) , the Yarra Pygmy Perch *Edelia obscura* (Klunzinger), and Ewen's Pygmy Perch *Nannoperca variegata* Kuiter and Allen (Wager and Jackson 1993). The carp is thought to compete with several more common indigenous fishes for food (Fletcher *et al.* 1985). Finally, carp have been implicated as a secondary factor in the decline of native gastropods in the Murray River, South Australia. While river regulation is considered to have the greater impact, habitat alterations caused by carp may have changed the food available to indigenous aquatic snails (Sheldon & Walker 1993).

Grass Carp, *Ctenopharyngodon idella* (Valenciennes), although not introduced specifically for aquaculture purposes, is an herbivorous species that has had unforeseen adverse effects on the environment. By feeding selectively on more palatable species, it may shift the flora towards tougher species which are more of a nuisance than the plants originally targeted for control. There is also concern that the removal of plant beds may eliminate the spawning habitat of phytophilous species, the refugia of young fish and amphibians, and the feeding habitat of certain water birds (Welcomme 1988).

Damage to physical habitat is less well established as an ecological impact of exotic species; structural damage has largely been reported because of its impact on human enterprises rather than natural resources. The Louisiana Red Crayfish *Procambarus clarkii* (Girard), indigenous to the United States, has been introduced for aquaculture purposes to Kenya, Uganda, the Sudan, Japan, parts of Europe, Hawaii and south and central America (Welcomme 1988). In Europe it was introduced to replace *Astacus astacus* L. in natural waters after the devastation of this indigenous species by the European crayfish plague caused by the oomycete fungus *Aphanomyces astaci* L. *Procambarus* is regarded as a pest in many areas because of its burrowing behaviour and the underground galleries it creates may cause extensive damage to earthen irrigation structures and the banks of aquaculture ponds. Its introduction to Japan as a food supply for bullfrogs resulted in damage to rice crops by its feeding on the plants and undermining of rice field dykes (Pillay 1992). The Chinese or Mitten Crab, *Eriocheir sinensis* M. Edw., accidentally introduced into inland European waters in the ballast of ships, causes similar structural problems along river banks.

In Australia, the Yabby *Cherax destructor* (Clark) has a wide natural distribution in central and southern inland areas. Recreational and commercial fisheries operate within its natural range and aquaculture activities are carried out both within the natural range and in Western Australia (Kailola, Williams, Stewart, Reichelt, McNee A. and Grieve 1993). However, the Tasmanian Inland Fisheries Commission has declared the Yabby a noxious species and opposes its introduction because of the crayfish's potential to damage irrigation channel and dam walls by burrowing, and to cause the deterioration of water quality in farm dams. There is also concern about the risk of disease transmission and competition with indigenous species of crayfish. On Kangaroo Island off the coast of South Australia, indigenous species of shrimps are rarely found where translocated Yabby have become well established (P. Suter, pers. comm.).

There may be many more instances of aquatic habitat deterioration caused by exotic species, but such effects tend to be noticed mainly when they interfere with human property and production systems. It is also worth emphasising that the effects of introduced species on water quality and habitat are frequently masked by changes brought about by human activities. In the Murray-Darling River system, the direct impact of carp on turbidity levels has been difficult to distinguish from natural variations in turbidity associated with flooding and drying sequences, and from the effects of accelerated catchment and bank erosion on suspended solids levels (Fletcher *et al.* 1985).

Disturbance of the Natural Community

Disruption of the surrounding biotic community produced by species interactions associated with aquaculture operations may occur in a number of ways. Predation and competition are the principal processes involved. However, the effects of attraction to aquaculture facilities and the collection of wild seed or broodstock may also contribute significantly in some cases. Often the causal elements are unknown or obscured by other factors, such as pollution or habitat alteration. Causal processes rarely operate unilaterally, most being inseparably interrelated. Introduced piscivorous predators, for example, are reported to interact with indigenous biota by various types of competition (exploitation, interference, spatial) as well as predation, and these interactions will vary throughout the ontogeny of the predator.

The end result of such interactions, irrespective of the particular causal processes, is the impoverishment of diversity. For example, in the Philippines, the exotic catfish, *Clarias batrachus* (L.) is reported to have displaced the indigenous catfish *C. macrocephalus* Günther (Juliano, Guerrero and Ronquillo 1989). In India, the indigenous carps *Catla catla* (Ham. Buch.) and *Labeo rohita* Hamilton are reported to have declined in certain reservoirs due to the introduction of Silver Carp, *Hypophthalmichthys molitrix.* (Valenciennes) (Shetty, Nandeesha and Jhingran 1989). In Malaysia, the Snakeskin Gouramy, *Trichogaster pectoralis* (Regan) is reported to have displaced the indigenous congener, *T. trichopterus* (Pallas) to some extent (Ang, Gopinath and Chua 1989).

Wild caught feed, broodstock and seed

Carnivorous species under culture conditions require large quantities of animal protein, and this is often supplied from wild caught stocks. For example, Iwama (1991) indicates that 6 kg of herring are needed to produce 1 kg of rainbow trout. Increasing demand for wild caught feed may lead to overfishing and conflicts with other users of the resource.

A number of aquaculture species are grown from wild caught seed stock. The Milkfish, *Chanos chanos*, and penaeid prawns are examples of these (Iwama 1991; Barg 1992; Phillips, Kwei Lin and Beveridge 1993). In Bangladesh, the collection of wild carp fry for stocking freshwater fish ponds is reported to have contributed to the decline of fish stocks (Beveridge and Phillips 1993). Over exploitation of the wild caught resource is an ever-present possibility. At the same time, other, non-target species also suffer considerable losses which result from post-larvae harvesting. Studies have indicated that wasted bycatch (the fry and larvae of non-target species) can be 10 - 50 times the biomass of the collected post-larvae (Macintosh and Phillips 1992).

Prawn culture also requires the collection of individuals in breeding condition, for the production of nauplii. As these are animals of marketable-size, their collection has led to competition between harvest fishery and aquaculture interests. Protective sanctions have been required in a number of countries, for example, the Philippines and Indonesia, to protect stocks from overfishing (Lee and Wickins 1992).

Attraction to Culture Operations

Beveridge and Phillips (1993) indicate that aquaculture structures such as cages and pens may act as fish aggregation devices. In addition, many species are attracted to aquaculture operations by the excess food which is generally available in the vicinity (Weston 1991). Enriched conditions caused by excess food often produce a succession in the abundance and diversity of biota attracted to aquaculture operations. Such conditions can lead to enhanced populations of indigenous or escaped fishes in the areas surrounding aquaculture operations as much as 12 times higher than distant, unaffected sites (Iwama 1991; Weston 1991).

Predators attracted to aquaculture operations include birds, snakes, monitor lizards and turtles, fish, dolphins, rodents, mustelids and bears (Beveridge 1984; Iwama 1991). Predators may be attracted to culture facilities by the shelter they provide, and by the increased abundance of food provided by the culture species themselves, by fouling organisms and by indigenous prey species. In their efforts to access caged stock, aggressive or large predators can cause structural damage to enclosures and so greatly increase the possibility of escapes (Iwama 1991; Munday *et al.* 1992a).

Disease outbreaks in cultivated stock may also be increased by predators attracted to aquaculture facilities. While bird attacks may often be unsuccessful, a not inconsiderable number of caged fish are wounded by such attacks. Under the normally crowded culture conditions, such damage increases the susceptibility of the fish to bacterial or fungal infections (Beveridge 1984; Iwama 1991). Predators may also act as intermediate hosts of parasites, or assist in the transfer of pathogens. In several cases in the United Kingdom, caged trout have developed severe infestations of the cestode *Diphyllobothrium*, resulting in heavy mortalities and the closure of one farm (Wooten 1979). The rapid spread of this parasite from its indigenous hosts was partly due to the migration of large numbers of gulls (*Larus* sp.) into the area (Beveridge 1984). Birds act as the intermediate host of the nematode *Contracaecum* sp., a common parasite of tilapia, as well as being responsible for many digenean infections of fish (Roberts and Sommerville 1982).

Predation

Species interactions involving predation may be the most obvious (Courtenay 1990) and readily documented impact of exotic species, and they often result in the complete elimination of indigenous species in parts of their range. Globally, introduced salmonids and piscivorous species such as Largemouth Bass, *Micropterus salmoides* (Lacepede), are particularly notorious.

The Rainbow Trout, *O. mykiss*, is reported to be responsible for declines in indigenous fishes in Peru, Colombia, Chile, Yugoslavia, Himalayan rivers, South Africa and New Zealand (Welcomme 1988). In Lesotho, South Africa, *O. mykiss* preys on, and competes for food with, the rare indigenous minnow, *Oreodaimon quathlambae* (Barnard) (Bruton and van As 1986). The Rainbow Trout has been shown to prey on the Australian Barred Galaxias, *Galaxias fuscus* Mack, an endangered species (Wager and Jackson 1993), and the distributions of *O. mykiss* and *Galaxias olidus* Günther in the Australian Capital Territory appear to be mutually exclusive (Lintermans 1991), presumably due to predation. Trout have had similar impacts on the distribution of the common River Galaxias, *G. vulgaris* Stokell in New Zealand streams (McDowall

1990). In Autralia, *O. mykiss* is suspected of predation on at least two vulnerable indigenous fishes; *E. obscura* and *N. variegata* (Wager and Jackson 1993). A paucity of indigenous fish species has been reported in areas where trout occur in the south-west areas of Western Australia (D. Morgan, pers. comm.)

The Brown Trout has also had a major impact on indigenous fish species and is implicated in the decline in numbers of four endangered, four vulnerable, and one species with a poorly known distribution in Australia (Wager and Jackson 1993). *S. trutta* is suspected of adversely interacting with the endangered Pedder Galaxias, *Galaxias pedderensis* Frankenberg, causing a dramatic decline in numbers. However, this decline is also linked to invasion by the translocated Climbing Galaxias, *Galaxias brevipinnis* Günther (Wager and Jackson 1993).

Invasive predatory fishes, such as bass (*Micropterus* spp.) and trout (*O. mykiss* and *S. trutta*) have been implicated in the decline or local extinction of eight species of minnow (Cyprinidae), the Cape Kurper, *Sandelia capensis* (Cuvier) and *Kneria auriculata* (Pelligrin), some of which are classed as rare and endangered species in South Africa (Skelton 1993).

Competition

Exploitation competition is often invoked as the mechanism underlying the decline of indigenous fish species in areas where exotic species become established and abundant. This form of interaction occurs as a result of a shortage of some critical resource required by the competing organisms. The resource is usually food or space (i.e. the physical habitat required for spawning, foraging and other activities). Competition may alternatively involve a collection of effects termed interference, including territoriality, poisoning, injury or death by encounter (Schoener 1986) and inhibition of reproduction. The two types of competition are often imperfectly distinguished in descriptions of the interactions of exotic and indigenous species. Exploitation competition is notoriously difficult to demonstrate in the field, and most of the examples of impact attributed to competition have no experimental basis.

In spite of these difficulties, there is a strong belief that exotic species frequently out compete indigenous species to the point of causing a considerable reduction in abundance, or even their complete disappearance. The Brown Trout is reported to have competed with, and displaced, indigenous salmonids in North America, and is actively excluded from some locations to facilitate the rehabilitation of populations of indigenous salmonids, including Brook Trout, *Salvelinus fontinalis* (Mitchill) and Atlantic Salmon, *Salmo salar* L. (Clugston 1990).

The decline of indigenous fish species in Tashkent (former USSR) has been reported (Welcomme 1988, citing Rosenthal 1976) as a result of exotic species accidentally introduced with Grass Carp. Welcomme (1988, citing Noble 1980) noted that several indigenous species have been unable to compete with introduced tilapiine cichlids in southern USA. In the Tyume River, Eastern Cape Province, South Africa, a rare species of Kurper, *Andelia bainsi* Castelnau, is threatened by introduced Rainbow Trout, Largemouth Bass and the translocated Sharptooth Catfish, *Clarias gariepinus* (Burchell), which compete for food and space (Bruton and van As 1986).

In parts of tropical Asia the tilapia, *Oreochromis mossambicus* (Peters), contributes significant proportions of the animal protein available to local communities. In 1988 this species produced in excess of 100 000 tonnes from capture fisheries and aquaculture operations (Petr 1992). However, in many Asian countries where this species has been introduced it is now considered a pest fish because of its invasive abilities, lack of social acceptance, and its propensity to overpopulate eutrophic waterbodies with masses of stunted individuals (Blühdorn and Arthington 1992). Stunted populations tend to crowd out established species in aquaculture systems and harvest fisheries by restricting living space, and in extreme cases, may cause asphyxiation by creating an oxygen deficiency in the water column (Welcomme 1988). Several countries now regard *O. mossambicus* as unsuitable for culture (China and Malaysia) or as a pest (India, Taiwan, and the Philippines) (De Silva 1989). Tilapias have interfered with the development of aquaculture in the Philippines and on several South Pacific islands (Nelson and Eldredge 1991).

Competition for breeding space has adversely affected the indigenous tilapia *O. variabilis* (Boulenger) in Lake Victoria, where introduced *Tilapia zillii* (Gervais) share the same nursery habitats (Welcomme 1988). Australian studies of the distribution and abundance of *O. mossambicus* have indicated the potential for competition with indigenous species for food and breeding territories, and stunting has occurred both in disturbed and relatively pristine habitats (Blühdorn, Arthington and Mather 1990; Arthington and Blühdorn 1994). *O. mossambicus* is considered to have the potential to devastate indigenous fish populations if it moves down the Darling River system from Queensland (P. Gehrke, pers. comm.) and is regarded as probably the most serious threat currently facing the Murray-Darling River system (B. Lawrence pers comm.).

In Australia, the decline and fragmentation of galaxiid populations has been attributed to interspecific competition with *S. trutta* for food (Fletcher 1979; Jackson and Williams 1980), and the blackfish, *Gadopsis marmoratus* Richardson may have been similarly affected (Fletcher 1986), although in neither case was the role of predation entirely eliminated. Brown Trout compete for food with the vulnerable indigenous Macquarie Perch, *Macquaria australasica* Cuvier and Valenciennes, and possibly prey on the juveniles of this species (Wager and Jackson 1993).

Mussels in large-scale farming systems in coastal lagoons, bays and inlets may compete with indigenous filter-feeders for planktonic food organisms and thus seriously affect their recruitment (Chua 1993). Suspended mussel culture in the Ria de Arosa, Spain, is reported to have replaced copepods as the principal pelagic grazing organism (Barg 1992). Intensive raft culture of the mussel, *Mytilus edulis* L., in north-west Spain has changed the patterns of plankton composition and production, and the infaunal benthic community is affected by heavy organic enrichment from faecal wastes. However, the organic particulates move out onto the coastal shelf and support an enriched benthic community that may provide a significant food resource for demersal fishes (Tenore, Corral, Gonzalez and Lopez-Jamar 1985).

Interference competition has been described in relatively few instances, but the Brown Trout has been implicated in aggressive interactions with indigenous salmonids in the USA (Taylor *et al.* 1984).

Genetic Interactions

Escaped aquaculture species may interact with indigenous species by breeding with local populations of the same species or through hybridisation with closely related species (Munday *et al.* 1992a; Beveridge and Phillips 1993). The escape of transgenic species from aquaculture facilities is regarded as a further dimension of the threat to indigenous biota arising from introduced species (Kapuscinski and Hallerman 1991).

Amongst the salmonids, there is good evidence of interbreeding between escapees from fish farms and local populations; for example, in southern Norwegian rivers, up to 28% of spawning Atlantic Salmon, *S. salar,* may be of farmed origin (Munday *et al.* 1992a).

Wild Atlantic Salmon populations show marked morphological differences between rivers and local populations of salmonid fishes tend to be adapted to their specific environments (Munday *et al.* 1992a). Such adaptation is maintained by natal stream homing of the adult fish. Many traits in Atlantic Salmon have a heritable genetic basis, including growth rate, age of maturation and smolting, egg size, timing of sea migration and migratory behaviour at sea (Institute of Aquaculture 1990). Thus there is concern that the adaptive traits and reproductive fitness of genetically distinct wild stocks may be significantly affected by interbreeding with introduced fish which escape from fish farms (Beveridge and Phillips 1993).

Studies in Sweden, France, Spain, Ireland, Canada and the USA have reported interbreeding of escaped Brown Trout and Rainbow Trout with indigenous populations; introgression rates of up to 80% have been recorded in France (Munday *et al.* 1992a). The observed effects of interbreeding vary from no measurable impact on the genetic structure of local stocks, to partial or complete displacement of genetically distinct indigenous populations with homogeneous hatchery fish (Munday *et al.* 1992a).

Hybridisation may be a serious threat posed by both exotic and translocated aquaculture species, since interbreeding of closely related species often produces viable offspring (Welcomme 1988). Hybridisation of Atlantic Salmon and Brown Trout has been reported in Canada and Spain (Munday *et al.* 1992a) and in Australia under hatchery conditions (Fletcher 1986). Welcomme (1988) reported that the stresses associated with introduction may lead to a breakdown in normal behaviour and the formation of hybrids between species and even genera which do not normally hybridise when they coexist in the wild.

Interbreeding has occurred in Australia between two varieties of the European Carp introduced for aquaculture, producing the vigorous Boolara strain which spread explosively in the 1960s and 1970s and became far more widespread and problematic than any of the original stocks (Shearer and Mulley 1978; Brumley 1991).

Much of the world's inland aquaculture uses carps and tilapiine cichlids and there has been widespread spontaneous and deliberate interbreeding of different genetic strains and species (Welcomme 1988; Wohlfarth and Hulata 1983). The wild genetic resources of both groups of fishes are believed to be threatened, and this may be true of catfishes and other groups (Pullin 1993b). Localities identified in 1987 (Pullin 1988) for collection of pure stocks of tilapias in Africa have subsequently been found to contain fish of mixed origins, probably as a result of interbreeding with exotic stocks escaping from failed aquaculture ventures (Pullin 1993b). In a different instance, feral *O. mossambicus* were responsible for the commercial failure of the culture of all-male hybrids of *O. mossambicus* x *O. hornorum* (Trewavas) in Malaysia, because stray feral stock contaminated the hybrid stock, effectively eliminating any advantages of mono-sex culture (Ang, Gopinath and Chua 1989).

In Taiwan, the exotic catfish,*C. batrachus* is reported to have hybridised with the indigenous congener, *C. fuscus* Lacepede. This hybrid has spread over much of the island, reportedly to such an extent that the pure form of *C. fuscus* is in danger of extinction (Liao and Liu 1989). The conservation of wild genetic diversity in its own right and for future uses is steadily becoming a serious issue in many countries.

Beveridge and Phillips (1993) and Weston (1991) note that there have been very few studies of genetic interactions between escaped aquaculture species and wild stocks. Assessment of the potential risk of adverse genetic effects has been attempted for salmonids, especially the Atlantic Salmon (e.g. Hindar, Ryman and Utter 1991), although Munday *et al.* (1992a) consider that a better understanding of the genetics and population dynamics of wild Atlantic Salmon is required before impacts due to interbreeding and loss of adaptiveness can be assessed.

Transgenic species have been produced for aquaculture, but little is known of their potential effects and considerable research is required before they are widely used in aquaculture (Beveridge and Phillips 1993). The use of transgenic species in aquaculture and the potential transfer of genetic material to indigenous stocks and species introduces another element into the management of aquaculture species. However, Kapuscinski and Hallerman (1991) state that the ecological impacts of both fertile and sterile transgenic fish will depend more on their overall phenotypic performance than on specific genetic constructs inserted into their genomes.

Introduction of Diseases and Parasites

The dissemination of disease agents and parasites has accompanied the introduction and translocation of fish, crustaceans and shellfish throughout the world and the management of pathogens is a serious issue in all countries with a large investment in aquaculture. For example, European Carp in North America are reported to harbour 170 parasites of which 138 are exotic species; they include algae, fungi, protozoans, flatworms, tapeworms, leeches and crustaceans, most of which occur in crowded or aquaculture conditions (Clugston

1990). A summary of the pathogens which may be transferred with Rainbow Trout, Atlantic Salmon, eels, oysters, mussels and lobsters is given by Munday et al. (1992a).

Certain pathogens are considered to affect only their original host species, genus or family, so the introduction of an infected species within the group may threaten other members present in the receiving country, in aquaculture systems or in the wild. The bacterial causative agent of furunculosis was probably introduced into the United Kingdom from Denmark with Brown Trout, and spread through movements of farmed trout (Pillay 1992). It was subsequently imported to Norway via salmon smolts from Scotland and has spread to indigenous populations of salmonids (Egidius 1987). Wild Atlantic Salmon populations in Norway have suffered massive mortalities and, in some areas, total eradication caused by the monogenean fluke, *Gyrodactylus* sp., introduced from infected salmon hatcheries in Sweden (Munday *et al.* 1992a; Pillay 1992).

The re-introduction of the European flat oyster, *Ostrea edulis* L., from North America spread the oyster parasite *Bonamia* sp., which devastated the European flat oyster industry (Barg 1992). The introduction of commercial prawn species was linked to the spread of pathogens such as Infectious Haematopoietic Necrosis Virus (IHNV) and Monodon Bacilovirus (MBV) (Barg 1992). MBV was responsible for the collapse of prawn culture in Taiwan in 1988 (Kwei Lin 1989).

Increasingly there are incidences where taxon or species-specific diseases are transmitted to unrelated hosts. Furunculosis was introduced to Victoria, Australia, in the 1970s via infected Japanese goldfish (Trust, Khouri, Austin and Ashburner 1980). This episode brought goldfish ulcer disease to cultured and wild Australian goldfish and carp populations - an issue of some significance for the aquarium industry and aquaculturists. It was followed by restrictions on the movements of goldfish within Australia as a protection against disease in important salmonid fisheries; Tasmania for example requires that imported goldfish be certified free of goldfish ulcer disease (Langdon 1990).

The spread of imported pathogens from their exotic hosts to indigenous species is of relevance to environmental protection and may exact a high ecological and economic cost. However, the evidence of impacts on indigenous species is limited (Munday *et al.* 1992a; Pillay 1992).

Langdon and Humphrey (1987) described a new viral disease of unknown origin, Epizootic Haematopoietic Necrosis Virus (EHNV), affecting cultured Rainbow Trout and feral Redfin Perch, *Perca fluviatilis* L. in Australia. This disease is known to be highly pathogenic to several indigenous Australian fishes, including Silver Perch, *Bidyanus bidyanus* (Mitchell), Mountain Galaxias, *G. olidus* and Macquarie Perch, *Macquaria australasica* Cuvier and Valenciennes, and to a lesser extent, Murray Cod, *Maccullochella peeli* (Mitchell) (Langdon 1989). The translocation of Redfin Perch and salmonids by angling and government bodies without health certification thus poses a threat to valuable indigenous fish stocks in the wild.

Massive mortalities of cultivated Silver Barramundi, *Lates calcarifer* Bloch due to a picornia-like virus, BPLV (Glazebrook, Heasman & de Beer 1990), have recently caused havoc to the industry in Queensland and the

Northern Territory. BPLV has been diagnosed from Barramundi in Australia (Glazebrook *et al.* 1990; Munday *et al.* 1992b), as well as from stocks in Thailand and Tahiti. Recent applications to establish growout facilities for Silver Barramundi within the Murray-Darling Basin have been refused because there is preliminary evidence that Macquarie Perch, Murray Cod and Silver Perch are susceptible to BPLV (Dr. J. Glazebrook, pers. comm.). Asymptomatic carriers of BPLV have been detected in Barramundi from South Australian hatcheries and one of the urgent issues is the development and ready availability of a sensitive and specific test for the detection of the virus in asymptomatic fish.

Infectious agents may be more pathogenic to atypical hosts. Similarly, they may cause clinical disease only in atypical hosts. Such infectious agents become a problem when the typical host species come into contact with unusual hosts. Examples are whirling disease in Rainbow Trout, proliferative kidney disease of salmonids and the North American crayfish plague fungus. This fungus is only mildly pathogenic to the host crayfish but has devastated native European astacids.

Thompson (1990) illustrated the spread of the crayfish plague throughout Europe and discussed the pathology of the fungus and the ecological consequences of the loss of endemic crayfish species as a result of the plague. He cites the introduction of the plague vector animal, the North American Signal Crayfish, *Pacifastacus leniusculus* Dana, as an outstanding example of deleterious translocations, and lists irreparable shifts in species diversity, ecosystem stress, and damaged traditional fisheries as major impacts of the fungus imported via this species. One of the side effects of the crayfish plague was that decimation of the indigenous Swedish crayfish, *A.. astacus*, allowed macrophytes such as *Chara* spp. and *Elodea canadensis* Rich., to proliferate, resulting in the elimination of game fish habitat (Thompson 1990).

Parasites may also be transferred from exotic species to indigenous forms. Parasites introduced with the exotic Pacific Oyster, *Crassostrea gigas* L., including the Japanese Oyster Drill, *Ocenebra japonica*, the oriental copepod *Mytilicola* sp. and the oyster flatworm, *Pseudostylochus* sp., are reported to have had serious adverse impacts on oyster stocks on the west coast of the USA (Clugston 1990; Barg 1992). Moyle (1986) noted that indigenous Californian fishes seemed to be more heavily parasitised by exotic parasites (e.g. the anchor worm, *Lernaea cyprinacea* L.), than exotic fishes. The anchor worm is now common in several native Australian fishes (Lloyd, Arthington and Milton 1987).

Disease organisms may be transmitted from wild populations to cultivated species (Roberts 1985) because the stressful nature of aquaculture may render cultivated species relatively susceptible to infections. Such interactions, and those between exotic species and indigenous pathogens are not well understood (Munday *et al.* 1992a). The role of predators in the transmission of diseases and parasites from the wild to cultivated species is also poorly documented (e.g. see Beveridge 1984).

Socio-economic Perspectives

The perception of species interaction effects has a firm foundation in socio-economic conditions. A farmer in a developed country may be looking to diversify production, the manager of a multi-million dollar sea-cage enterprise will look for high profitability, a subsistence fisherman in an undeveloped country may be simply trying to feed his family. Each of these people will have a different perspective on species interactions resulting from escapes from their culture enterprise, or attractions to it. The first may view escapes from unfenced, littoral ponds as an 'act of God' and an occurrence for which there is little financial or regulatory incentive to guard against (Thompson 1990). The second may view the destruction of cages by storms as an engineering problem, to be solved by the sufficient input of resources. The third may view locally abundant exotic species as a gift, promising an improved food supply (Beveridge and Phillips 1993).

An example of contrasting perspectives on escaped aquaculture species is given by Clugston (1990). The carp, *C. carpio*, is generally considered a trash fish in the USA. However, carp persists under degraded habitat conditions in some urban areas and provide opportunities for recreational fishing which would otherwise not be available. The tilapia, *O. mossambicus*, is generally considered to be a pest throughout Asia (Welcomme 1988), although this is not the case in Sri Lanka (De Silva and Senaratne 1988). However, even in some of those countries which officially consider this species a pest, nuisance, or trash fish, feral stocks are an important source of food (Blühdorn and Arthington 1992). For example, in Indonesia, *O. mossambicus* is reported to be very useful for small-scale fish farmers and low income groups, but is considered a competitive trash fish in more intensive aquaculture (Eidman 1989). In the Asian region, *O. mossambicus* remained the dominant species in capture fisheries and provided a significant contribution to aquaculture production in 1988 (Petr 1992).

The Asia-Pacific region produced 84.5% of global aquaculture products in 1990 and, unlike post-industrial countries, most of this production was destined for local markets (Cvasas 1993). Such markets are, by nature, conservative and will often reject new or non-traditional products, thus generating considerable market resistance to otherwise nutritionally suitable products (Liao and Liu 1989: Cvasas 1993). Thus, as Welcomme (1988) explained, an unbiassed, objective assessment of the effects of an introduced species may be impossible to achieve, and local perceptions of the costs and benefits of an introduction must be taken into account when considering such effects.

Effects of Culture Systems on Species Interactions

The likelihood of escape from aquaculture facilities is generally a function of the value of the product rather than of any regulatory prohibitions. Thus, intensive aquaculture operations tend to have fairly expensive and relatively effective means for preventing escape. On the other hand, subsistence aquaculture operations generally have few barriers to escape, since they often rely on locally occurring organisms to provide seed stock. In the past, government agencies have actively supported the wide distribution of favoured species for semi-intensive and extensive culture irrespective of the organism's status as exotic or not.

Extensive Culture

Extensive culture involves the rearing of organisms under relatively natural conditions of habitat and water quality. Generally, no supplementary feed is provided and stocking densities are low. Extensive culture is usually a supplement to other activities for income generation or subsistence, and is conducted principally in tropical areas using planktivorous species, because of the high natural productivity of these regions (Iwama 1991).

Extensive prawn culture consumes large areas of mangroves for low productivity returns (Phillips et al. 1993). It involves the passive recruitment of seed stock which is often unpredictable and scarce as the resource succumbs to overuse and other pressures, such as pollution and destruction of mangroves (Macintosh and Phillips 1992).

In extensive culture there are few barriers to the exchange of species with the external environment. The implications for species interactions are twofold. Firstly, escaped organisms generally consist of the same stocks as those in the surrounding environment, since this is often their source, so the environmental impact of such escapes will be minimal, although disease transfer remains a potential problem. Secondly, because of this close interaction between the aquaculture environment and surrounding waters, any exotic which becomes feral will, sooner or later, find its way into the culture environment. The impact of such an event will depend on the perspective of the farmer. The invading feral tilapia, *O. mossambicus*, is reported to have disrupted the extensive brackish water farming of Milkfish, *C. chanos* in the Philippines. However, *O. mossambicus* is now an established species in brackish water farms in that country (Juliano *et al.* 1989).

Semi-intensive Culture

Semi-intensive culture involves the rearing of organisms under controlled habitat conditions, although artificial containers are rarely used (Iwama 1991). The diet is supplemented and stocking densities are elevated above natural levels. Semi-intensive systems are used to produce low to high value product, often in conjunction with other aquatic species (polyculture) or other animals and plants (integrated culture), mainly in tropical areas.

Semi-intensive culture is a favoured approach in developing countries as it treads the middle ground between the high capital costs and economic risks of intensive culture and the requirement for large areas of land for extensive culture (Pullin 1989; Phillips *et al.* 1993).

Species interactions arise in the collection of seed and broodstock from the wild, and the escape of exotic organisms into the local aquatic environment. The demand for seed stock in prawn aquaculture has given rise to commercial production of post-larvae, which may alleviate some of the demand on the wild stocks. However, Macintosh and Phillips (1992) reported that the poor quality of hatchery reared post-larvae in some areas had resulted in the shunning of such stocks with preference given to wild caught post-larvae, again increasing the demand on a diminishing natural resource.

Intensive Culture

Intensive culture involves the rearing of organisms under high stocking densities with active disease control measures. Diet is completely controlled, as are the habitat and water quality. Such systems aim to produce high value product concomitant with the high investment costs and risks involved. High value means that there is a strong economic incentive not to lose stock. For example, the high value of Largemouth Bass, *M. salmoides* in Taiwan has prompted great care to be taken to prevent its escape into natural waters. These precautions have prevented the adverse environmental effects reported for this species elsewhere from occurring in Taiwan (Liao and Liu 1989).

However, when escapes from intensive operations do occur, the high stocking densities mean that many organisms are released into the outside environment. Similarly, the high stocking densities attract greater numbers of predators and the large amounts of unconsumed food attract scavengers.

Intensive culture is practiced predominantly in the temperate waters of developed countries, where it is used to produce large volumes of high value fin fish in cage, raceway, and pond systems. In these locations the principal causes of stock losses are bad weather, floods, vandalism, and marauding animals (mammals, piscivorous birds, mustelids). Species interactions arising from these operations include hybridisation of escapees with indigenous congeners, disturbance to the natural community through predation, competition, and attraction to the aquaculture structures and excess food resources, and the spread of disease and parasites.

In tropical countries, the principal intensive culture operations are centred on prawn production. In developing countries, such enterprises often suffer disease and effluent problems under intensive culture conditions, and present significant economic barriers for small-scale farmers (Phillips *et al.* 1993).

Management of Species Interactions

In its broadest sense, the management of species interactions originating from aquaculture operations is the management of exotic or translocated species. There are a number of cogent reviews of this topic (Courtenay and Stauffer 1984; Bruton and van As 1986; Turner 1988; Welcomme 1988; De Silva 1989; Pollard 1990; Billington and Hebert 1991; Crowl *et al.* 1992). However, layers of political, social and economic policy intervene between the fundamental ecological impacts of invasive species and the management approaches actually applied to such problems.

In developed countries, the establishment and operation of aquaculture ventures are regulated, and regulations are enforced to a much greater extent than in developing countries (Cvasas 1993). The management of species interactions in developing countries will therefore depend less on government-imposed sanctions and more on the availability of appropriate methodologies for aquaculture planning, guidelines for site selection, and public sector support for research, development and extension services (Cvasas 1993; GESAMP 1991). The aim of aquaculture operations in all countries should be the development of sustainable systems that avoid environmental harm (Pullin 1993b).

Select Appropriate Scales of Operation

While intensive culture is reasonably successful in developed countries, it is generally less so in developing countries where such highly capital intensive operations are out of the reach of small-scale farmers who represent the most numerous and needy group of potential aquaculturists in this area of the world (Pullin 1989). Based on the premise that, "Poverty and environmental conservation cannot co-exist", Pullin (1993a) recommends that small-scale (household/ village) semi-intensive aquaculture systems are the most socially and environmentally desirable for developing countries.

The demands of expanding urbanisation in these countries will probably require the development of some large-scale operations, but most of the technical advice and policy formulation for aquaculture development should be attuned to the specific needs and opportunities of small-scale systems, rather than being constrained by foreign cultural biases (Pullin 1993a).

Two other factors which affect aquaculture in developing countries are the fallacies that indigenous species are inferior and not worth developing for local aquaculture, and that 'short-cutting' protocols on introductions is desirable because exotic species add prestige to aid-funded projects (Pullin 1993b).

Use Sterile Stock Where Possible

Organisms which have been chemically or chromosomally sterilised have been used to achieve specific purposes in aquaculture without most of the risks involved in using fertile specimens. Triploid grass carp, for example, have been used for vegetation control in North America (Clugston 1990). Much of modern tilapia culture is carried out using infertile stock.

Research the Effects of Escapees

Research into the effects of species interactions is scarce, especially in relation to aquaculture in developing countries where it is, arguably, the most needed (Pullin 1993a). There is also no generally applicable method for predicting the effects of escapes in any of the areas in which aquaculture is practiced (Pullin 1993b). This lack is further exacerbated by the often inadequate timeframes of the research that is conducted (Pullin 1993b). For example, the European carp, *C. carpio*, was introduced to Australian waters some 100 years before its massive invasion of the Murray-Darling River system in Australia (Brumley 1991).

Improve Quarantine Measures

The introduction of the crayfish plague caused by the fungus *Aphanomyces astaci*, along with the exotic North American signal crayfish, to Britain was the result of poor quarantine mechanisms. Legislatively, there were no laws preventing the importation of live animals, and regulations governing quarantine and escape prevention at aquaculture sites were ineffective

(Thompson 1990). Operationally, token measures to prevent escape of the crayfish were ineffective, as were quarantine measures to prevent the release of viable fungal spores from the aquaculture site (Thompson 1990). As well as devastating the European crayfish industry, this fungus is reported to be capable of infecting other crayfish species, such as the Red Claw, *Cherax quadricarinatus* von Martens, an indigenous Australian species (Lee and Wickins 1992).

International Protocols for Introductions

The growing awareness of problems arising from the establishment in the wild of exotic species originally introduced for aquaculture has encouraged the investigation of indigenous species, especially in wealthier countries. Whilst this may prove of great benefit, both economically and in terms of environmental care, for the host country, the more promising species and successful culture systems are likely to be marketed internationally, and may be introduced eventually to other countries, setting in train new waves of movement. Here international codes of practice can be brought into play.

Protocols on introductions allow the potential risks and benefits of introductions to be compared, and decisions to be made in the light of existing scientific knowledge (Coates 1993). The adoption of precautionary policies and codes of practice, such as those proposed by the FAO (Anon. 1994) and others (Neal 1984; Turner 1988), and their widespread implementation, will be a major step in developing a standardised approach to introductions and in facilitating a measure of consensus about likely species interactions. However, this will mean that hard decisions will have to be made about the traffic in promising new candidates for aquaculture, at the cost of lost profits for the country of origin, and the receiving country.

Summary

In conclusion, it is evident that a number of factors concerning species interactions arising from aquaculture activities are common across all types of operations. The two most fundamental elements can be the most simply stated: escapes are inevitable and invasions are irreversible. Thus, any cultured organism is a potentially invasive species.

The impacts of species interactions associated with aquaculture have, in some cases, resulted in alterations to the host environment and disruptions to the host community which result in impoverishment of diversity, genetic disturbances, or the introduction of parasites and diseases. The effects of these impacts are filtered through socio-economic factors to produce often divergent perspectives about escaped organisms in particular, and aquaculture in general. These local perspectives are vital indicators of the types of management, scale of operations, and effectiveness of the regulatory sanctions which can be applied successfully.

Internationally, protocols exist to help determine whether a species should be introduced to a new environment. These should be adhered to rigorously and improved as time and experience determine. Nationally and locally, the risks involved in escapes from (or attractions to) aquaculture operations can be minimised by careful site selection, appropriate containment facilities and operations geared for sustainability, with environmentally responsible approaches applied to the stocked organisms and their husbandry, quarantine, effluent control and disease management.

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