# Ecological risk assessment and management of exotic organisms associated with aquaculture activities

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**ABSTRACT**

Ecological risk assessment (ERA) can be defined as a logical and systematic process for objectively defining the probability of an adverse effect (or impact) on an organism or collection of organisms when challenged by an environmental modification such as introduction of exotic organisms. Aquaculture activities have been thought to be one of the major pathways for introducing exotic aquatic species that may become established as nuisance or pest species. This review provides comprehensive guidelines in ecological hazard identification, risk analysis methodologies, risk management and communication in relation to the introduction of exotic species, particularly those with the potential to become established pests. The best strategy for minimizing impacts from invasive species is to prevent their introduction and their subsequent release or escape into the environment. Effective ERA processes are, therefore, needed to identify most or all potentially invasive species and restrict their introduction or use in aquaculture, while encouraging the use of species that have low invasion potential and can provide net economic benefits for the aquaculture industry and society at large. Both qualitative and quantitative ERA approaches are described in this review, but more emphasis is placed on the former because of its simplicity and practicality. Given the fact that data availability has a huge influence on the quality and confidence of the risk assessment, it is essential to put more effort and funding into basic research on the life histories, population dynamics and ecology of aquaculture organisms and establish better regional and

international information systems concerning these species. Most importantly, concerted efforts should be made to educate consumers and industries about the ecological risk and economic impacts of invasive organisms, and mandate implementation of legally binding species-specific risk assessments and risk management so as to reduce the risks of biological invasion through aquaculture activities.

## INTRODUCTION

Ecological risk assessment (ERA) can be defined as the process of determining the nature and likelihood of effects of anthropogenic actions on animals, plants and the environment (SETAC, 1997; USEPA, 1998). In more precise terms, ERA is a logical and systematic process for objectively defining the probability of an adverse effect (or impact) on an organism or collection of organisms when challenged with an environmental modification such as habitat destruction, chemical contamination, invasion of exotic species, infection with disease organisms or some other potential stressor (Newman, Roberts and Hale, 2001; Sergeant, 2002). In 1998, the United States Environmental Protection Agency (USEPA) published the Federal Guidelines for ERA (USEPA, 1998), which provides the basic terminology, concepts, assessment framework and step-by-step procedures of ERA, with special emphasis on assessing ecological risks of chemical contamination. In general, ERA includes four key phases:

- problem formulation (i.e. identification of hazards and sensitive receivers);
- parallel analysis of exposure and effect (i.e. pathway and risk analysis);
- risk characterization; and
- risk management and communication.

Such a framework has been recently adopted to assess ecological risks associated with aquaculture activities (e.g. Visuthismajarn *et al.*, 2005; Colnar and Landis, 2007). For instance, the Working Group 31 on Environmental Impacts of Coastal Aquaculture of the IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) has examined the issue of risk assessment of coastal aquaculture with the objectives of promoting harmonization and consistency in the analysis of risk and uncertainty, and improving risk communication (Hambrey and Southall, 2002). Although this GESAMP report covers many important topics such as ERAs for pollutants released from the farms, alternation of benthic communities beneath the farm and interaction of farmed fish with wild populations (Chapter 9; Hambrey and Southall, 2002), it does not deal with ecological risks arising from diseases originating in farmed animals or the introduction of exotic species.

## HAZARD IDENTIFICATION IN AQUACULTURE

### Ecological (pest) hazard identification

There are diverse operational systems in aquaculture, ranging from inland pond culture to offshore ocean culture with submerged cages (Table 1). The major farming species also vary, including various finfish, shrimp, crab, lobster, oyster, mussel, snail, abalone and sea cucumbers. Different operational systems and farming species pose different ecological risks to the surrounding natural environment (Table 1). These ecological risks can be broadly classified into seven categories:

- habitat alternation or destruction;
- organic pollution and eutrophication;
- chemical contamination with pesticides and therapeutics;
- infection with disease organisms;

TABLE 1

**Ecological risks associated with various aquaculture operation systems. Anticipated relative risk levels are indicated with abbreviations**

| Ecological hazard | | Inland closed systems (freshwater) | | Semi-open systems in wetland/ mangrove (brackishwater) | | Open-water systems (lakes or coastal waters) | | | | Offshore open-ocean systems |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Fish pond | Shrimp/crab/ snail pond | Fish tidal pond | Shrimp/crab/ sea cucumber tidal pond | Open-water cages/ net-pen or fish | Open-water cages for shrimp/crab | Bivalves on lines or in cages | Clams on natural sandy shore | Submersible cages for offshore finfish |
| 1 | Habitat alternation or destruction | M | M | V | V | H | H | H | H | H |
| 2 | Organic pollution and eutrophication | L[1] | L[1] | V | V | H–V[2] | H–V[2] | L–M[2] | L | M |
| 3 | Chemical contamination with pesticides and therapeutics | L | L | V | V | V | V | N.A. | N.A. | M–H |
| 4 | Genetic risks of escaped culture animals | M–H | M–H | V | V | V | V | V | V | V |
| 5 | Introduction of exotic "contaminant" species | V | V | V | V | V | V | V | V | V |
| 6 | Infection with disease organisms | H | H | H | H | H | H | H | H | H |
| 7 | Use of wild pelagic fish for feed | L–H[3] | L–M | H | L–M | H | L–M | N.A. | N.A. | V |

[1] Assuming that effluent and sediment are treated before reuse or disposal.
[2] The risk level depends on the stocking density.
[3] The risk level would be reduced if polyculture mode is adopted (i.e. farming herbivores, omnivores and carnivorous fishes in the same pond).

Legend: V – very high risk; H – high risk; M – moderate risk; L – low risk; NA – not applicable

- genetic risks of escaped culture animals;
- depletion of wild fish stock to provide food for cultured carnivorous fish; and
- introduction of exotic species.

The overall ecological risks of inland closed-culture systems with proper confinement are anticipated to be comparatively low provided that the effluent and any contaminated sediment are treated and handled properly (Table 1). In contrast, tidal-pond, open-water cage (or net-pen) and offshore ocean culture systems pose relatively higher ecological risks because of the direct contact between the farms and adjacent aquatic environments. Wastes are directly discharged to the natural habitat, while farmed animals can more easily escape from the farm to the environment through human errors (e.g. escape during transfer between cages, so called "leakage") or episodic events (e.g. storms or tropical cyclones) (Table 1). As other articles in this proceedings deal with the ecological risks associated with pollution from farm wastes and chemicals (Phillips and Subasinghe, 2008, this volume), pathogens and diseases (Reantaso and Arthur, 2008, this volume), as well as the genetic risks from escaped organisms (Hallerman, 2008, this volume), this article primarily aims to provide comprehensive guidelines in ecological hazard identification, risk analysis methodologies, risk management and communication in relation to the introduction of exotic species, particularly those with the potential to become established pests or nuisance organisms.

***Definition of hazards associated with introduction of exotic species***

Accidental or intentional introductions of non-native species have become an alarming global environmental problem, because many of these introduced non-native species are able to establish, spread and eventually become nuisance and/or invasive beyond their natural ranges (Elton, 1958; Sugunan, 1995; Kolar and Lodge, 2001; Jeschke and Strayer, 2005; De Silva *et al*., 2006; Soto *et al.,* 2006). In some cases, these introduced organisms become competitors that deplete or exclude native species where their niches overlap, through competition for space or food. In other instances, they may drive native species to extinction through direct predation. For example, the introduction of the predatory Nile perch (*Lates niloticus*) in the 1950s into Lake Victoria, East Africa, has been cited as causing the extinction of more than 200 native fish species (Reinthal and King, 1997). Similarly, there is evidence that the introduction of predatory fish into the Sepik River, New Guinea, in an attempt to enhance fisheries stocks, has been associated with the decline of indigenous species (Dudgeon and Smith, 2006). Other biological impacts of invaders include interbreeding between escaped aquaculture animals and wild conspecifics (Youngson *et al.,* 2001), transmission of disease and/or parasites (Snyder and Evans, 2006) and alternation of community structure. Chen (1989) reported that the introduction of grass carp (*Ctenopharyngodon idellus*) in Donghu Lake in Wuhan, People's Republic of China, dramatically reduced submerged macrophytes, resulting in ecological changes that brought about increases in the abundance of silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Aristichthys nobilis*) but, more importantly, the disappearance of most of the 60 native fish species in the lake.

Apart from these ecological impacts, the establishment of invasive organisms may have social and economic impacts. Introduced salmonids in southern Chile, for example, resulted in substantial changes in the abundance and distribution of native fishes, with profound consequences for fishing practices and fisheries management (Soto, Jara and Moreno, 2001). The economic impacts included the costs of losing natural resources and the environmental services they support (e.g. native species and biodiversity) and controlling the nuisance species.

Once invaders establish in the wild, it is extremely difficult to eradicate them, and such control measures are often very costly and ineffective. For example, the United States and Canada together spend about US$ 15 million annually to control the sea lamprey (*Petromyzon marinus*) in the Great Lakes (Goddard, 1997). The overall economic costs of invasive species in the United States alone have been estimated at US$ 120 billion annually (Pimentel *et al.,* 2000, 2005). Furthermore, 42 percent of the species on the threatened or endangered species lists in the United States are at risk primarily because of exotic invasive species (Pimentel, Zuniga and Morrison, 2005). It is a reflection of the ecological and economic impacts of biological invasions that a number of treaties and agreements (obligatory and voluntary) exist at the international and regional levels to provide legal instruments and institutions for prevention and control of invasive species. Those concerned with aquatic taxa are listed in Annex 1.

Aquaculture activities are considered one of the major pathways for introducing non-native aquatic species that may become invasive (Weigle *et al.*, 2005; Casal, 2006). First, exotic species that are deliberately introduced for culture may subsequently escape from the farm and establish themselves as nuisance organisms in the wild. Introduction of tilapias (Cichlidae: *Oreochromis*, *Tilapia* and *Sarotherodon*) as foodfish in fresh or brackishwater aquaculture systems, for example, has resulted in significant ecological and economic impacts in the tropics and subtropics (Canonico *et al.,* 2005). Secondly, farmed species such as oysters, clams and mussels can harbour other exotic "contaminant" species (including pests, parasites and pathogens) on their shells, in their tissues or associated with sediments in their bodies or mantle cavities (Minchin, 1996). Therefore, aquaculture-related transfers of half-grown oysters between countries can result in the unintentional introduction of exotic species and pathogens (see examples in Minchin, 1996).

Once exotic species have been introduced, there is a significant likelihood that they will become invasive species. Jeschke and Strayer (2005) have estimated that approximately one in four vertebrate introductions becomes invasive. Consequently, the best strategy for minimizing impacts from invasive species is to prevent their introduction and their subsequent release or escape into the environment (Weigle *et al.,* 2005). Effective risk assessment processes are needed to identify most or all potentially invasive species and restrict their introduction or use in aquaculture, while encouraging the use of species that have low invasion potential and can provide net economic benefits for the aquaculture industry and society at large (Keller, Lodge and Finnoff, 2007). Leung *et al.* (2002) have estimated that if the introduction of the zebra mussel (*Dreissena polymorpha*) had been prevented by spending US$0.32 million in risk assessments and prevention measures, the benefits to the United States of America would far exceed the US$0.5 million spent annually in managing this established invader. In addition to more effective risk assessments of potential invasiveness of candidate species before introduction, improved management and practices in handling and transport of aquaculture organisms (e.g. appropriate packaging in transportation, effective quarantine and sterilization of water from shipping containers), as well as education and communication with the practitioners and stakeholders are needed.

***A conceptual model and essential information for hazard identification***

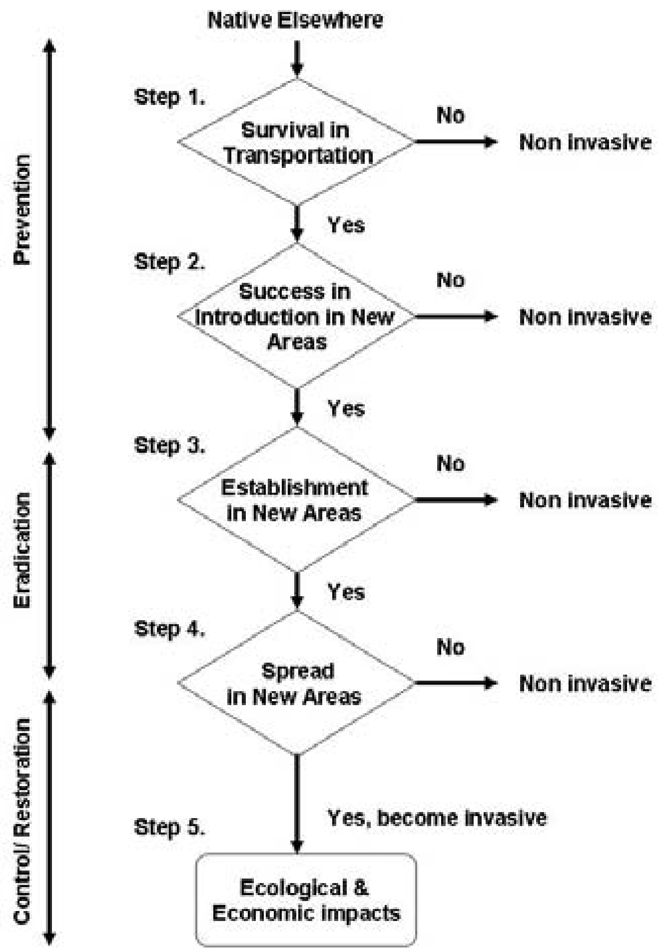
It is of utmost importance that regulatory authorities, risk assessors and risk managers understand the processes involved in the introduction, establishment and spread of exotic species in aquaculture industries before beginning risk analysis. The invasion sequence typically follows five key steps:

(1) individuals of the target species are collected and transported from their native geographical range to new locations where they do not occur naturally (they must survive handling and transportation stresses);
(2) the target species is introduced into the new location where it is an exotic species (the introduction may be intentional or unintentional);
(3) individuals become established at the point of introduction;

(4) the established population subsequently grows and spreads to other locations; and
(5) the invaders became a nuisance and cause ecological and economic impacts (Figure 1).

It is theoretically possible to predict and assess the invasion risk of the candidate species based on this model by way of multiple-level evaluations of the survival probability in Step 1, the chance of introduction via different pathways (e.g. accidental escape) in Step 2, the chance of establishment in the wild in relation to environmental conditions (e.g. temperature, salinity and food availability) in Step 3, and the likelihood of spread in Step 4. Information required for an effective risk assessment includes species-specific biological and ecological information such as invasion history of closely related species; life-history parameters and lifecycle pattern, mobility, feeding habits and habitat occupancy in the native environment, including tolerance limits of temperature, salinity and other physicochemical factors. Also essential are data related to the proposed introduction, such as the quantity of introduced organisms, frequency of introduction, handling practices and the aquaculture operation system

FIGURE 1
**A typical invasion sequence of exotic species, with the corresponding management options (prevention, eradication and control/restoration) at different stages**




Source: Modified from Kolar and Lodge, 2001; Sakai *et al.*, 2001.

(Risk Assessment and Management Committee, 1996; Kolar and Lodge, 2002; Kelly, Drake and Lodge, 2007).

## RISK ASSESSMENT METHODS IN AQUACULTURE – OVERVIEW AND SOME EXAMPLES

### Ecological risk assessment for introduction of exotic species

Current ecological risk assessment protocols can be classified into either qualitative or quantitative approaches. Both approaches are principally built upon the skeleton of the invasion sequence presented in Figure 1. The former approach is based on largely qualitative categorizations of putative diagnostic characteristics of invasive species, all available relevant information (see above) and weight-of-evidence judgement by experts. Detailed guidelines and protocols of this qualitative approach can be found in the *ICES Code of Practice on the Introductions and Transfers of Marine Organisms* (ICES, 2004), the *Generic Non-indigenous Aquatic Organisms Risk Analysis Review Process* (Risk Assessment and Management Committee, 1996) and the *Weed Risk Assessment of Australia* (Groves, Panetta and Virtue, 2001).

In contrast to the qualitative approach, quantitative methods are more sophisticated, as they require extra efforts in data mining, and technical inputs from experts on mathematical modelling and statistical computation (Kolar and Lodge, 2001). Given the benefit of more published studies on biological invasions over the last 15 years, more data allowing the development of quantitative methods for risk screening of exotic organisms have become available, making it possible to identify the major biological characteristic(s) of invasive species that predict invasion risk. These advanced computation-intensive approaches are more powerful than the qualitative approach and provide quite accurate prediction of invasive species with >80 percent accuracy (Kolar and Lodge, 2001; Keller, Drake and Lodge, 2007).

Despite the relative success of the quantitative approach, quantitative methods are complex and require highly-skilled personnel for implementation. On the other hand, qualitative methods are highly flexible and relatively easy to follow, and are thus more likely to be adopted by regulatory authorities worldwide. Since there is an urgent need to implement risk analysis in aquaculture, simple and practical methods are needed so that the process can begin and, it is hoped, prevent biological invasions from aquaculture activities as soon as possible. Once this generic, qualitative approach is established, the method could be gradually improved and advanced by incorporating quantitative elements. Accordingly, this review places more emphasis on the qualitative approach, whereas the quantitative approach is only briefly described.

#### *Qualitative risk analysis*

The method described herein originates from the *Generic Non-indigenous Aquatic Organisms Risk Analysis Review Process* (hereafter referred to as the Review Process) that was developed by the United States Federal Aquatic Nuisance Species (ANS) Task Force in 1996 (Risk Assessment and Management Committee, 1996). As the Review Process also provides detailed information on the history and development of the exotic pest risk assessment, risk analysis philosophy and additional notes regarding the risk assessment protocols, we have not repeated this material here.

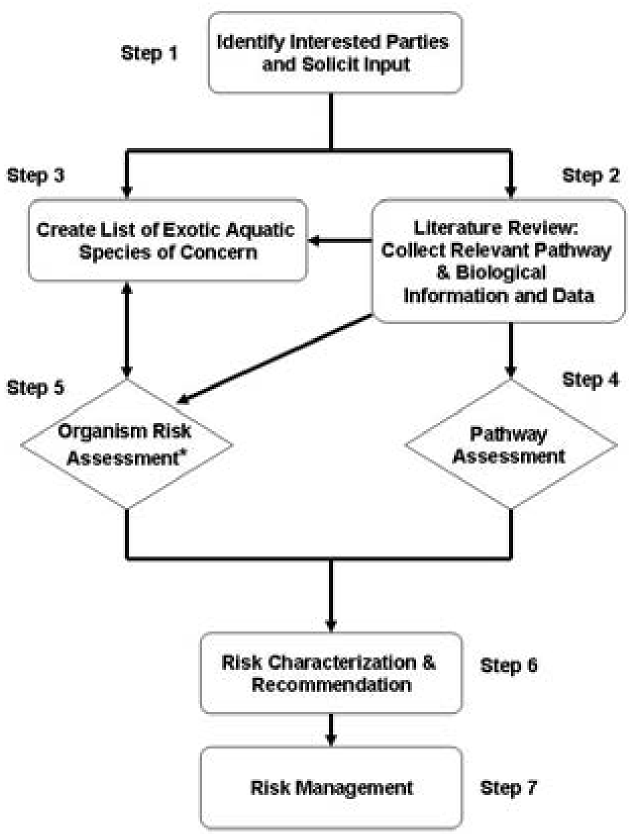
In accordance with common aquaculture practices, slight modifications of the Review Process have been made in this paper with a view to providing comprehensive, user-friendly guidelines for risk analysis of invasiveness of exotic species. The objective is to evaluate the risk of introducing exotic organisms into a new environment via a standardized process, but it may also provide recommendations for appropriate mitigation and/or risk management options. Like the conventional ecological assessment framework (USEPA, 1998), the qualitative risk analysis also comprises:

(i) problem formulation;
(ii) risk analyses (referred to as Pathway Analysis and Organism Risk Assessment in this paper); and
(iii) risk characterization.

***(i) Problem formulation and assessment framework***

Biological invasion risk is a sum of the risks incurred in the transportation, introduction, establishment, spread and impact stages along the sequence of biological invasion (Figure 1). The qualitative risk analysis should comprise two major components, namely Pathway Analysis and Organism Risk Assessment (Figure 2; the Review Process). To initiate the risk assessment process, the regulatory authority should identify interested parties such as governmental officials, practitioners, representatives from related non-governmental organizations (NGOs), academics, biological invasion experts and other related stakeholders who will provide valuable input and comments on the risk assessment processes (Figure 2; Step 1). Such an initiation step is vital, as this will improve communication of potential risks among all parties, reduce bias and make the processes more open and transparent to the general public. Both components require extensive and comprehensive literature reviews on the pathway-related matters (e.g. history, ecological risk and mitigation measures) and information on the biology, ecology and invasion history of the species of concern (Figure 2; Step 2). In addition, projected information such as the quantity, life stages and exact origin of the organisms is needed for both pathway and organism analyses. It will be advantageous if the

FIGURE 2
**A conceptual framework for the qualitative risk assessment for introduction of exotic organisms. (*details of the organism risk assessment are presented in Figure 3)**



receiving country or region has already created a list of exotic aquatic species (Step 3) and an archive of their biological and ecological data, as well as invasion history. Such a database will greatly help to speed up the analysis. Based on all available information, the corresponding risk of each invasion step (i.e. introduction pathway, establishment and spread, as well as ecological and economic impacts) is assessed through the standardized Pathway Analysis and Organism Risk Assessment (Steps 4 and 5) based on the principle of weight-of-evidence by a group of experts (Menzie *et al.*, 1996). Subsequently, the overall risk of the intended introduction of the exotic species can be characterized using a standardized rating scheme (Step 6). The results can be used to formulate appropriate mitigation measures and improve risk management (Step 7).

### *(ii) Pathway and organism risk analyses*

*Pathway analysis*

Pathway analysis is largely conducted through collection of relevant information. The following is a generalized list of information required for the pathway analysis:

- Describe the introduction pathway (intentional vs. unintentional introduction).
- Determine mechanism and history of the pathway.
- Determine the exact origin(s) of organisms associated with the pathway.
- Determine the numbers of organisms and species travelling with the pathway.
- Determine the intended use of the exotic organisms (as animal feeds or culture organisms for food and/or aquarium trade).
- Review the history of past experiences and previous risk assessments (including international examples) on the pathway or similar pathways.
- Review past and present mitigation actions related to the pathway.

As mentioned previously, there are two major pathways of introducing exotic organisms through aquaculture activities: intentional introduction of exotic species as culture organisms that eventually enter the natural environment (usually via accidental escape) and unintentional introduction of exotic organisms associated with imported culture organisms or live foods for aquaculture feed. It is important to evaluate the likelihood of escape within the intentional introduction pathway, particularly, in relation to the aquaculture system and facilities. In general, closed-circulation land-based systems pose relatively lower probability of escape in contrast to open-water systems, which have very high risks. Current management practices for minimizing escape of farmed organisms should be carefully reviewed with special reference to local conditions. Unintentional introductions are more likely associated with bivalve aquaculture because of the risk from associated "hitchhiker" organisms (see above; Minchin, 1996). Different handling processes can result in very different risks of biological invasion. If the organisms have undergone a quarantine procedure (e.g. brine dip of transfers) and are transported in reduced density, the risk of bringing in exotic species will be lower (Minchin, 1996). In some cases, traditional methods for packing shellfish can be problematic. For instance, many exotic species such as the green crab (*Caricinus maenas*) and the algae *Codium fragile* are believed to have been introduced to North America because they were among seaweeds used to pack shipments of bait worms (Weigle *et al.*, 2005). In addition, shipment containers usually contain water that may include juveniles, larvae or eggs of exotic species. If such water is disposed of in the new aquatic environment, it may give exotic organisms an opportunity to establish. Proper sterilization of such water (e.g. through boiling) is needed before discharge. Better codes of practice (e.g. ICES, 2004) should be followed by the aquaculture industry to control such risks. In addition, a risk assessment that reviews and examines the current practices of handling and transportation of shellfish is needed to generate accurate risk predictions. As the unintentional pathway shows a particularly high potential for introducing exotic organisms, it should trigger an in-depth risk analysis.

TABLE 2
**Classification of native and exotic species according to their characteristics. The priority of concern for each category is also given**

| Category | Organism characteristics | Concern |
|---|---|---|
| 1a | A species is exotic and not present in the region or country. | Yes |
| 1b | An exotic species, which has already been present in the region or country, is capable of further expansion. | Yes |
| 1c | An exotic species is currently present in the region or country and has reached probable limits of its range, but is genetically different enough to warrant concern and/or able to harbour another exotic pest. | Yes |
| 1d | An exotic species present in the region or country has reached probable limits of its range, and does not show any of the other characteristics of 1c. | No |
| 2a | A native species but is genetically different enough to warrant concern and/or able to harbour another exotic pest, and/or capable for further expansion. | Yes |
| 2b | Native species is not exhibiting any of the characteristics of 2a. | No |

*Source*: Risk Assessment and Management Committee, 1996.

*Creating a list of exotic aquatic organisms of concern*

In Step 3 (Figure 2), a list of exotic species of concern can be developed by identifying the species associated with the pathway, and then classifying them into in one of the categories listed in Table 2. Subsequent Organism Risk Assessments should be conducted for any listed species in categories 1a, 1b, 1c or 2a. The Food and Agriculture Organization of the United Nations' (FAO) Database on Introductions of Aquatic Species (DIAS) includes records of species introduced or transferred from one country to another and contains additional taxa, such as molluscs and crustaceans and marine species (http://www.fao.org/fi/website/FISearch.do?dom=introsp). If the exotic organisms are fish species, the risk assessor may visit and check relevant information in FishBase (Froese and Pauly, 2007; http://www.fishbase.org), which has a section dealing with invasive species associated with aquaculture and the aquarium trade and providing the origin and invasion history of exotic species in different countries. Furthermore, the Global Invasive Species Database which is managed by the Invasive Species Specialist Group (ISSG) of the International Union for the Conservation of Nature (IUCN) Species Survival Commission also provides useful information for the Organism Risk Assessment, such as a searchable database on invasive aquatic species, with references and links to relevant websites (www.issg.org/database).

*Organism risk analysis*

This manual follows the convention of considering any species as invasive that not only becomes established, but also spreads readily in its new range (Elton, 1958). Invasive organisms must be able to pass through all the key stages (Steps 1–5 in Figure 1) along the sequence of successful biological invasion. The Organism Risk Assessment element in Figure 2 (Step 5) is the most important component of the Review Process used in evaluating and determining the risk associated with a pathway. The Risk Assessment Model (i.e. PIES-COM model) that drives the Organism Risk Assessment (Figure 3) has two major parts – the "probability of establishment" and "consequence of establishment", as described in the equations below:

$$\text{Invasion Risk} = \{\text{Probability of Establishment}\} \times \{\text{Consequence of Establishment}\} \quad (1)$$
$$\text{Invasion Risk} = \{P \times I \times E \times S\} \times \{C \times O \times M\} \quad (2)$$

Where

$P$ = Estimated probability of the organism being on, with or in the Pathway
$I$ = Estimated probability of the organism surviving in transit and Introduction
$E$ = Estimated probability of the organism colonizing and Establishing a population
$S$ = Estimated probability of the organism Spreading beyond the colonized area
$C$ = Estimated the Consequence of all possible ecological impacts if established

*O* = Estimated the Overall perceived impact from social and/or political influences
*M* = Estimated economic impact (i.e. Money) if established

This Risk Assessment Model contains seven essential elements (i.e. PIES·COM). The probability of establishment is a product of the probabilities of the pathway associated with the particular species (*P*), successful introduction (*I*), successful establishment (*E*) and spread of the species in the new environments (*S*) (Figure 3). The consequence of establishment includes the ecological impact potential (*C*), perceived impact from social and political points of view (*O*) and the economic impact potential (*M*) (Figure 3). The various elements of the PIES·COM model are portrayed as being independent of one another for model simplification, and the order of the elements in the model does not necessarily reflect the order of calculation. Based on the available information and experts' judgement on all relevant considerations (Table 3), a risk rating is given to each element in the model from one of the three levels: Low, Medium or High. As the certainty of such risk ratings will be influenced considerably by the available information and its quality and reliability, it is important to record the source of information to support the risk rating and state the degree of uncertainty that the assessor associated with each element. The degree of uncertainty can be classified into:

- Very Certain (VC): firm conclusion;
- Reasonably Certain (RC): reasonably convinced;
- Moderately Certain (MC): more certain than not;
- Reasonably Uncertain (RU): reasonably indecisive; or
- Very Uncertain (VU): a guess.

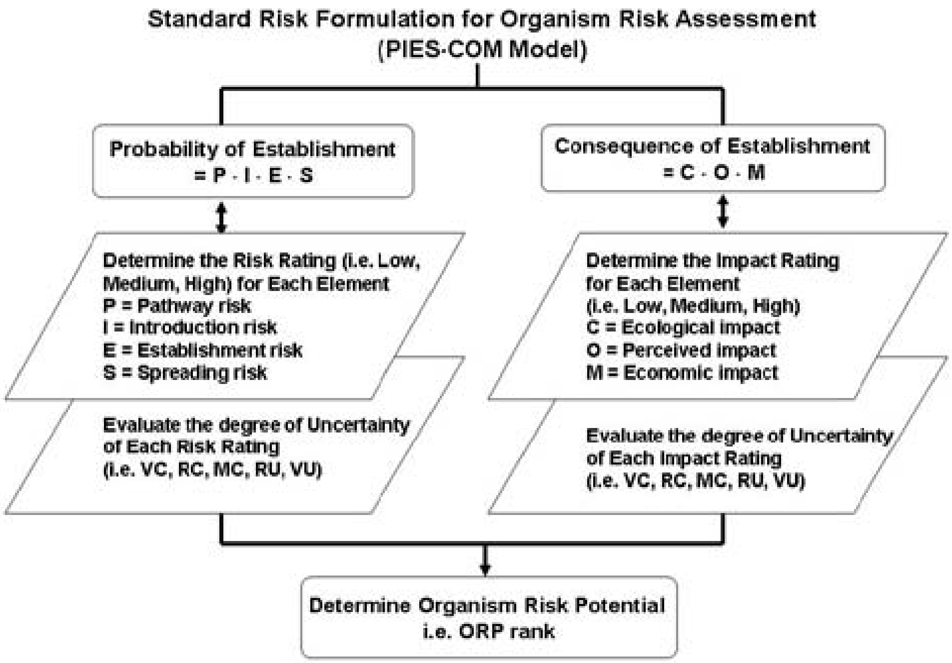
TABLE 3
**Characteristics and areas for consideration in the Organism Risk Assessment on the seven key elements (PIES·COM) in the Risk Model (see Figure 3)**

| Symbol | Element | Characteristics and assessment areas |
|---|---|---|
| **Probability of establishment** | | |
| P | Exotic organisms associated with the pathway | The assessor has to answer whether or not the organisms show a convincing temporal and spatial association with the pathway. |
| I | Exotic organisms surviving the transit | The assessor should examine the organism's hitchhiking ability in commerce, ability to survive during transit, stage of lifecycle during transit, number of individuals expected to be associated with the pathway or whether it is deliberately introduced. |
| E | Exotic organisms colonizing, establishing and maintaining a population | The assessor should investigate whether the organisms will come in contact with an adequate food resource, encounter appreciable abiotic and biotic environmental resistance, and have the ability to reproduce in the new environment. |
| S | Exotic organisms spreading beyond the colonized area | The assessor should evaluate whether the organisms have ability for natural dispersal, ability to use human activity for dispersal, ability to readily develop races or strains, and should estimate the range of probable spread. |
| **Consequence of establishment (CE)[1]** | | |
| C | Ecological impact | The assessor should consider the impact on ecosystem destabilization, reduction in biodiversity, reduction or elimination of keystone species, reduction or elimination of endangered/threatened species, and effects of control measures. |
| O | Perceived impact | These may include aesthetic damage, consumer concerns and political repercussions. |
| M | Economic impact | Consideration aspects include economic importance of the aquaculture practitioners, damage to natural resources, effects to subsidiary industries, effects to exports, ad control costs. |

[1] Notes: The elements considered under Consequences can also be used to record positive impacts that an exotic organism might have, for example, its importance as a biological control agent, aquatic pet, sport fish, scientific research organism or based on its use in aquaculture. The final risk rating will reflect a balance between the cost, the benefit and the risk of introducing the exotic organisms. When determining the CE score, the three elements are not treated as equal: C and M are given a higher weighting than O.

*Source*: Risk Assessment and Management Committee, 1996.

FIGURE 3
**A schematic diagram illustrating the Organism Risk Assessment with the seven key elements**




Legend: VC – very certain; RV – reasonably certain; MC – moderately certain; RU – reasonably uncertain; VU – very uncertain)

For elements with certainty at or below MC, it is important to obtain more data as soon as resources (time, money and efforts) permit. The accuracy of the risk analysis can be greatly improved by minimizing uncertainty. While recording the source and details of the information to support the risk analysis, a code of reference should be assigned for each cited document or information source. The reference codes may include:

- **G**: general knowledge, no specific source;
- **J**: judgement evaluation by experts only; or
- **E**: extrapolation; information specific to invasive species not available, however available information on related organisms has been applied.
- **(Author, Year)**: Literature cited.

It is important to stress that the outcome of an Organism Risk Analysis is very likely ecosystem specific (Kolar and Lodge, 2002). Therefore, the risk assessor must consider the potential introduction of the organisms with reference to local conditions such as heterogeneity of aquatic environments, hydrographic parameters, existing biological communities and climate, etc. The risk assessor may incorporate methodologies such as geographical information systems (GIS), climate and ecological models, decision-making software, expert systems and graphical displays of uncertainty in order to increase the precision of one or more elements in the Organism Risk Assessment Risk (Assessment and Management Committee, 1996).

Biological traits of exotic organisms can be potential predictors indicating whether or not they will be invasive. Although biological traits vary among different stages of invasion (Figure 1) and are likely taxonomic specific, some rules-of-thumb about criteria for successful exotic invaders can be generalized from peer-reviewed literature and are listed below. They may be used to inform the risk assessment, to prioritize management efforts and to further develop quantitative risk assessment models.

a) *Having high fecundity*: Keller, Drake and Lodge (2007) showed that fecundity of exotic molluscs is positively related to their invasiveness, and thus fecundity can be used as one of the key criteria to screen their likelihood of becoming invasive species. Females of any molluscan species with an annual per-female output exceeding 162 offspring are likely to become invasive. Based on this criterion, any broadcast spawner with high fecundity would pose a high risk of biological invasion. For example, apple snails (Ampullariidae: *Pomacea canaliculata*) have a minimum clutch size of ~100 eggs and are able to lay many clutches annually (Keller, Drake and Lodge, 2007); these highly invasive snails have spread across much of tropical East Asia since their introduction from South America (Cowie 2004).
b) *Fast-growing in the establishment stage*: Kolar and Lodge (2002) demonstrated that successful fishes in the establishment stage (Figure 1, Step 3) often grow faster than non-invasive species.
c) *Slow-growing in the spreading stage*: Fishes that spread quickly exhibit slower relative individual growth rates than those which spread slowly (Kolar and Lodge, 2002).
d) *Tolerant of wide ranges of temperature and salinity*: Successful fishes in the both establishment and spreading stages (Steps 3–4) are able to tolerate wider ranges of temperature and salinity than are fishes that fail to invade (Kolar and Lodge, 2002).
e) *Predatory invaders that eat a range of prey*: Invasive predatory species are usually non-specialists with respect to prey preferences and eat a wide range of prey types (Kolar and Lodge, 2002).
f) *Smaller and more eggs*: Invasive fishes generally have smaller eggs and more of them than non-invasive fishes (Kolar and Lodge, 2002; Keller, Drake and Lodge, 2007).
g) *With a history of invasion*: It is reasonable to assume that the probability of organism invasiveness increases if the species has a history of invasion (Kolar and Lodge, 2001, 2002).
h) *Exotic taxa distantly related to native species*: Strauss, Webb and Salamin (2006) studied all grass species in California and discovered that highly invasive grass species are, on average, significantly less related to native grasses than are introduced but non-invasive grasses. This hypothesis has yet to be tested for aquatic organisms, but it is noteworthy that the spread of tilapias in Asia is associated with a virtual lack of native cichlids (Sri Lanka, with two native cichlids, is the exception).
i) *High number of individuals released and many release events*: The probability of establishment of exotic species increases with the number of individuals released and the number of release events (Kolar and Lodge, 2001).

Examination of the attributes of an exotic aquatic molluscan species within its native home range before introduction can provide some indication whether it will breed and recruit within the new environment (Minchin, 1996). Studies on the morphology and behaviour of the intended introduction in relation to those eco-morphologically similar native species may greatly aid in identifying the likely effects of competition before an introduction takes place (Minchin, 1996). Studies of chromosome numbers can provide some indication of whether hybridization is possible between native and introduced species (Minchin, 1996).

### *(iii) Risk characterization*

*Determination of the organism risk potential*

The Organism Risk Potential (ORP) is generated from the probability of establishment (PE) and the consequence of establishment (CE): i.e. the risk ratings and impact ratings of the elements in Table 3. The PE is assigned the value of the element (among P, I. E and S) with the lowest risk rating; some examples are shown in Table 4. Such a conservative estimate of the probability of establishment is justified because each of four elements must be present for the organism to become established, and the degree of biological uncertainty for success at each step is often high (Risk Assessment and Management Committee, 1996). For determining the CE score, the three elements (C, O and M) are not treated as equal and the Economic Impact and Ecological Impact are given a higher weighting than the Perceived Impact. The key for obtaining correct CE scores under different impact rating combinations of the three elements is shown in Table 5. It is important to note that the element M (economic impact) can also be positive impacts. An exotic organism might have its importance as a protein source for human consumption, a biological control agent, an aquatic pet, a sport fish and/or a scientific research organism. Tilapias (e.g. *Oreochromis mossambicus* and *O. niloticus*) are a good example to illustrate this point. Although exotic tilapias have been regarded as invasive fish species in many parts of the world (Canonico *et al.,* 2005), they can have beneficial effects on human livelihoods in tropical Asia (De Silva *et al.,* 2004) where they are an essential protein source; this has given rise to their nickname of "aquatic chicken" in Sir Lanka and Indonesia (De Silva *et al.,* 2004, 2006). Obviously, there is a disparity in attitudes toward management of exotic species in tropical Asia, where maintenance of human livelihoods is a dominant consideration, and in other parts of the world (e.g. North America, Australia), where the beneficial effects of exotic species are of lesser concern and more emphasis is placed upon the conservation of native biodiversity (for further discussion, see Dudgeon and Smith 2006). It is therefore anticipated that different countries will give different rating to Perceived (O) and Economic (M) Impacts based on their own socioeconomic viewpoints. The final risk-rating for CE will reflect a balance between the costs, benefits and risks of introducing exotic organisms.

After calculation of PE and CE, all seven risk element estimates (P, I, E, S, C, O and M) can be combined into an ORP rating that represents the overall risk of the organisms being assessed. This ORP rating can be determined using the key shown in Table 6. The determination of ORP generally favours the environmental protection (following the precautionary principle), as a higher rating is given to borderline cases

TABLE 4
**Examples for derivation of the score for the probability of establishment (PE)**

| | Pathway | Introduction | Establishment | Spread |
|---|---|---|---|---|
| Scenario 1 | | | | |
| Risk Rating | High | Low | Medium | Medium |
| | | PE Score = Low | | |
| Scenario 2 | | | | |
| Risk Rating | Medium | High | High | Medium |
| | | PE Score = Medium | | |
| Scenario 3 | | | | |
| Risk Rating | High | High | Medium | High |
| | | PE Score = Medium | | |

TABLE 5
**Key for determination of the final score of the Consequence of Establishment (CE)**

| Scenario | Ecological | Economic | Perceived | CE Score |
|---|---|---|---|---|
| 1 | H | L,M,H | L,M,H | H |
| 2 | L,M,H | H | L,M,H | H |
| 3 | M | M | L,M,H | M |
| 4 | M | L | L,M,H | M |
| 5 | L | M | L,M,H | M |
| 6 | L | L | M,H | M |
| 7 | L | L | L | L |

Legend: Impact rating described as H – high; M – medium; L - low

*Source*: Risk Assessment and Management Committee, 1996.

(cases 2, 4, 6 and 8 in Table 6). This approach is needed to help counteract the high degree of uncertainty usually associated with biological situations (Risk Assessment and Management Committee, 1996).

*Determination of the pathway risk potential*

The overall pathway risk is a sum of pathway-associated risks along the total invasion sequence. The seven risk element ratings of ORP are employed to estimate the combined risk or Pathway Risk Potential (PRP). In practice, results of the rating distribution of the seven elements (e.g. 1 High, 3 Medium and 3 Low) for deriving the ORP are used to determine the final risk rating of the PRP as shown in Table 7. Thus, the PRP generally reflects the highest ranking ORP.

An example of the data sheet format for the Organism Risk Assessment, with step-by-step procedures, is given in Annex 2.

*Risk characterization based on ORP and PRP ratings*

Once the final rating(s) of ORP and/or PRP have been estimated, the risk characterization is decided following the definition of ratings given in Table 8.

In these risk-characterization procedures, the selection of low, medium and high ratings throughout various levels should mainly be driven by available information

TABLE 6
**Key for determination of the final rating of Organism Risk Potential (ORP)**

| Case | Probability of establishment | Consequence of establishment | OPR rating |
|---|---|---|---|
| 1 | High | High | = High |
| 2 | Medium | High | = High |
| 3 | Low | High | = Medium |
| 4 | High | Medium | = High |
| 5 | Medium | Medium | = Medium |
| 6 | Low | Medium | = Medium |
| 7 | High | Low | = Medium |
| 8 | Medium | Low | = Medium |
| 9 | Low | Low | = Low |

*Source*: Risk Assessment and Management Committee, 1996.

TABLE 7
**Key for determination of the Pathway Risk Potential (PRP) based on the rating distribution of the seven elements used for deriving the Organism Risk Potential (ORP)**

| Characteristics of the rating distribution of the seven elements used for deriving the ORP | PRP rating |
|---|---|
| 1 or more scored with High rating(s) out of the seven | High |
| 5[1] or more scored with Medium rating(s) out of the seven | High |
| 1–5[1] scored with Medium rating(s) out of the seven | Medium |
| All scored with Low ratings | Low |

[1] Note: The number 5 used in this table is arbitrary. The selection of value 4 or 5 is possible when the number of medium-risk organisms reaches a level at which the total risk of the pathway becomes high.

*Source*: Risk Assessment and Management Committee, 1996.

TABLE 8
**Risk characterizations based on the final rating of ORP or PRP**

| Rating of ORP or PRP | Definition | Actions |
|---|---|---|
| Low | Acceptable risk: organism(s) of little concern | • Introduction may be permitted<br>• No mitigation is required |
| Medium | Unacceptable: organism(s) of moderate concern | • Introduction should be banned or should be controlled via risk management<br>• Mitigation is required |
| High | Unacceptable: organism(s) of high concern | • Introduction should be banned<br>• Prevention rather than mitigation is mandated, and control measures should be considered. |

such as biological statements under each element. As the low, medium and high ratings of the individual elements cannot be defined or measured, they remain judgemental in nature. Indeed, the Risk Assessment and Management Committee (1996) has stressed that "it is important to understand that the strength of the Review Process is not in the element-rating but in the detailed biological and other relevant information statements that motivates them". The final estimate of ORP or PRP only provides a summary of the entire risk assessment and some guidance for the decisions about whether or not an exotic species should be introduced, or whether control measures should be in place for introductions that are allowed or whether measures should take place to mitigate the effects of exotic species that have already become established (i.e. retrospective risk assessment). However, the final decision made by the risk assessors should be based on a holistic approach coupled with the weight-of-evidence assessment.

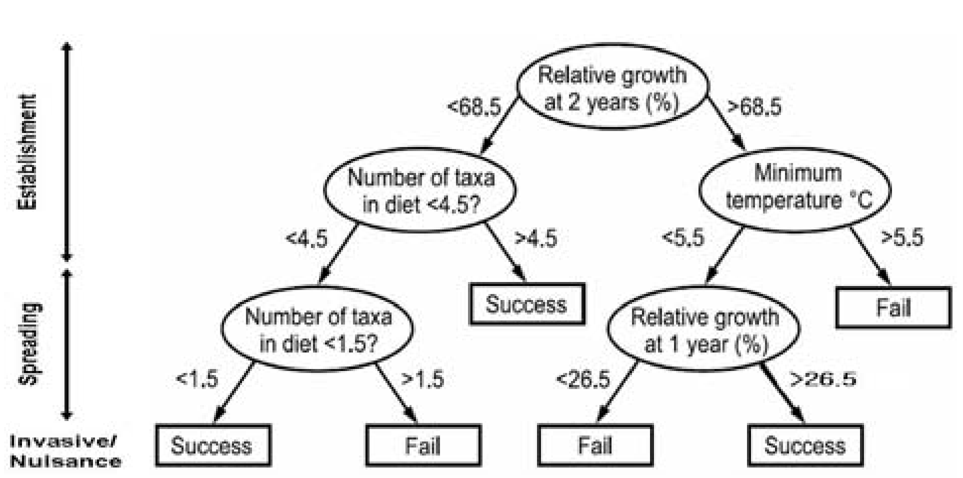
*Quantitative risk analysis*

Quantitative risk methods have been developed by Kolar and Lodge (2002) to quantify and predict the ecological risk of exotic freshwater fishes becoming invasive if they are introduced to North America. The methods are based on multivariate statistical methods including discriminant function analysis (DFA) and categorical and regression tree analysis (CART). Thirteen life-history characteristics, five habitat requirements and six aspects of invasion history and human use were used in the risk assessment model. DFA revealed the key features of fish species that were able to pass through the two main steps of the invasion process (establishment and spread; Figure 1): (1) successfully established fishes were fast growing, with a wide tolerance of salinity and temperature and a history of invasion; (2) quickly spreading fish species had a relatively slower growth rate and were tolerant of a wide temperature range and (3) successful invasive fishes have smaller eggs and wider tolerance for salinity and temperature. DFA allowed identification of the failed and successful fish species in each invasion stage with >80 percent accuracy (Kolar and Lodge, 2002).

CART is a model-based statistical technique involving model construction based on prior knowledge. Kolar and Lodge (2002) constructed their CART model for predicting invasive fishes with the critical values of minimum temperature threshold,

FIGURE 4

**Schematic diagram showing the CART model developed by Kolar and Lodge (2002). Invasion filters represent sequential stages of the invasion process through which a species must successfully pass if it is to pose and invasion risk to the new aquatic environment. The critical value for each filter (e.g. diet breadth: >4.5 prey taxa) is also shown**



dietary breadth and two measures of relative growth using information from literature and the results from their DFA analyses. The resulting CART model (Figure 4) assumed that established predatory fishes must growth faster (i.e. add >68.5 percent of initial body weight) within the first two years of introduction, have a wide dietary breadth (eat >4.5 prey taxa) and tolerate a minimum winter temperature of 5.5 °C (as prevails in the Great Lakes area) (Figure 4). For the spreading stage, the model assumes that rapidly spreading fishes have a slightly narrower diet breadth (<1.5 prey taxa) than in the establishment phase and a somewhat slower growth rate (add >26.5 percent of initial body weight). This CART model could correctly identify the species invasiveness for 43 out of 45 species inspected (Kolar and Lodge, 2002), which is very encouraging. Although this quantitative method requires more data input and advanced statistical analyses, it not only identifies potentially invasive species but also reveals essential biological traits that have significant correlations with invasiveness and may be useful criteria for screening risk. Like the qualitative analysis, uncertainties also exist in these quantitative methods (e.g. 5–20 percent error in the prediction; Kolar and Lodge, 2002), and therefore the results should be carefully evaluated with other available relevant information with respect to the key risk assessment elements described in the qualitative risk assessment (i.e. P, I, E, S, C, O and M).

Given the deterministic power of this quantitative method, many researchers have adopted or modified the approach of Kolar and Lodge (2002) in risk assessment for exotic aquatic organisms over the past few years (e.g. Rixon *et al.,* 2005; Jeschke and Strayer, 2005; Keller, Drake and Lodge, 2007; Miller *et al*., 2007). This risk assessment model can be even modified to account for the various life stages of exotic species under different climate scenarios. For example, Colnar and Landis (2007) have recently developed a risk assessment model for evaluation of invasiveness of various life stages (e.g. planktonic larval stages) of the introduced European green crab (*Carcinus maenas*) in North America in relation to habitat suitability and climate. Their model suggested that the risk of invasion impacts from *C. maenas* is substantially higher when El Nino-driven current dispersal is taking place.

Since 2002, at least ten articles using quantitative method in organism risk assessment for aquatic biological invasion have been published in peer-reviewed journals (Annex 3). Six of them are studies of fishes, two on molluscs, one on a crab species and one on marine fouling organisms. The frequency of studies of fishes probably indicates the generally greater availability of biological data. It also indirectly reflects the fact that these quantitative methods can be data limited. Increased data availability will certainly improve the predictive ability of the quantitative approach to organism risk assessments, as well as enhancing its popularity in management of biological invasion in the future. Note, however, that much of the data required for successful prediction is of the type generated by fundamental descriptive studies of growth and population dynamics, but investigations of this type are currently rather unfashionable and may be constrained by funding. Ultimately it may be the availability of such information, and not the complexity of the statistical models or the training required to use them, that will restrict the application of quantitative risk assessment approaches to predicting species invasiveness.

"All models are wrong, but some are useful" - a famous quote of George Box seems also correct with respect to the risk assessment models described above. In an important recent study, Ricciardi and Cohen (2007) have tested the relationship between the invasiveness of introduced species and their impacts on native biodiversity. They found no correlations between these variables for introduced plants, mammals, fishes, invertebrates, amphibians or reptiles. The results suggest that the mechanisms of invasion and impact are not strongly linked, and thus the probability of establishment and spread are not directly reflected by the impact of invasion. This may be good news, since it implies that highly invasive species do not necessarily have the strongest impacts. At present, quantitative methodologies seldom incorporate the impact analysis component in their models, and thereby omit some crucial elements (ecological, economic and perceived impacts) of risk prediction, making them less accurate. Fortunately, the qualitative risk assessment method (i.e. PIES·COM model mentioned above) not only examines the risk of organism invasiveness, but also explicitly considers the ecological, economic and perceived impacts resulted from biological invasion. Both quantitative and qualitative methods are, therefore, complimentary leading to a more holistic and accurate risk analysis.

## RISK MANAGEMENT IN AQUACULTURE

### Recommendations for ecological (pest) risk management

Management objectives inevitably depend on the stage of the biological invasion, whether at the prevention (i.e. risk assessment and education), eradication, or control and restoration stages (Figure 1). More attention should be paid to the risk prevention, to minimize the chances of an introduction or the necessity for eradication or control measures. Eradication is often impossible when the exotic organisms have already established (Kolar and Lodge, 2001), but the probability of establishment can be minimized if the recommendations made below are adopted.

1. ***Mandatory risk assessment.*** There is an urgent need to make Organism Risk Assessment a legally binding process in aquaculture industries, especially in Asia where >90 percent of the world's total annual aquaculture tonnage is produced (FAO, 2004). If this is not possible, regulatory authorities such as local governments and FAO should allocate more effort to educating consumers and aquaculture industries so that they understand the ecological and economic impacts of introducing invasive organisms, with the hope that this education will induce the industry to voluntarily follow the best code of practices (e.g. ICES, 2004).
2. ***Database of invasive aquatic organisms.*** The development of both global and regional databases of exotic species would greatly help management of introduced organisms (Michin, 1996; Casal, 2006). For instance, Bower *et al.* (1994) have reviewed the pests, parasites and pathogens of molluscs and listed a total of 45 species infecting oysters, 24 in clams and cockles, 18 in scallops, 17 in mussels and 4 in abalones. Such a list can provide an initial basis for the management of any introduction and transfer of marine molluscs. Once screening for known exotic species in consignments has been implemented, appropriate control/ mitigation measures can then be applied to minimize the chance of introducing nuisance species (Minchin 1996). At present, some international organizations have databases (e.g. FAO, IUCN and World Fish Centre) that provide generic information on invasive aquatic species. However, regional data and information on exotic species and their controls are usually limited and scattered in different peer-reviewed journals and local agency/project reports (Casal, 2006). It is often not an easy task for risk assessors to collate all relevant information for a particular organism. It has been suggested that an international database should be created through the use of Internet technology, sharing of databases or having a gateway or portal to which all introduced and invasive organisms-related databases link (Casal, 2006). The FishBase information system offers a good model.
3. ***Implementation of Codes of Practice***. Management practices designed to prevent releases of exotic organisms should be adopted in aquaculture industries (Weigle *et al*., 2005). A number of guidelines are available for management of introduction and transfer of aquatic organisms. Of these, the *ICES Code of practice on the introductions and transfers of marine organisms 2004* is the most relevant to aquaculture operations. The regulatory authorities should make this an essential

code of practice with which operators must abide and make efforts to promote its use if legislation is not possible.

4. ***Documentation of the movement of live aquatic organisms.*** It is essential to implement a mandatory reporting system documenting the details of any import and transportation of exotic organisms. More stringent requirements for reporting live species imports should be implemented (Weigle *et al.*, 2005), as such reporting can indicate the magnitude of international transport of organisms and the existing and/or potential threat faced by ecosystems due to species invasiveness (Casal, 2006).
5. ***Mandatory reporting system for escape.*** A mandatory reporting system for escapes will be vital for assessing the risk of introduction stage since, if escapes are not reported, the apparent risks of introduction cannot be estimated accurately. If the escape rates are high (i.e. higher than the accepted threshold), appropriate control measures should be implemented to rectify the problem. Accidental or episodic events of escape (e.g. due to bad weather or nets breaking) must be immediately reported to the risk management authority, which can then respond to the escape as quickly as possible through a mandated contingency plan involving capture or destruction of the escapees. Currently, few regions have implemented an escape-reporting system, and the requirement for reporting varies significantly among these regions (Annex 4; Naylor *et al.*, 2005). Significantly, there are no such requirements in Asia where most of the world's aquaculture takes place. Iceland, for example, has the strongest penalties (including the loss of aquaculture licenses) for failure to comply with escape-related regulations. In contrast, merely symbolic fines for major escape-events are levied in British Columbia, Canada, if the events are not reported promptly (Naylor *et al.*, 2005). Where possible, aquaculturists should keep a good record of any escape events (whether chronic "leakage" or episodic), with information such as the number, species, weather and date, and should inform the authorities as soon as possible after a major event.
6. ***Effective quarantine and wastewater sterilization.*** In general, companies that handle live shellfish require more scrutiny than those handling fresh finfish (Weigle *et al.*, 2005; Minchin, 1996), as many exotic organisms harboured by the shellfish may enter the new environment unintentionally. To reduce such risks, the organisms should be put through a quarantine procedure, while wastewater from shipping containers should be sterilized prior to discharge (Minchin, 1996; ICES, 2004).
7. ***Improvement of technology to reduce escape risk.*** Containment in farms should be improved so as to minimize the numbers of escapees (e.g. use of stronger net materials, tauter nets to deter seals; Naylor *et al.*, 2005). Emergency recovery procedures are also essential (see 5) as a back-up measure in the case of containment failure (Youngson *et al.*, 2001).
8. ***Development of artisanal fisheries on escaped exotic species.*** The chance of escaped populations of exotic organisms impacting native species may be reduced by allowing local artisanal fishing, as this can offer a way to control the population size of exotics if the fishing methods can be appropriated targeted (Soto, Jara and Moreno, 2001).

Recently, leading scientists in the field of biological invasion have put forward some important recommendations for improving the policy and management of biological invasions in the United States (Box 1; Lodge *et al.*, 2006). Many of these recommendations can also be applied in risk management for global aquaculture industries.

After completion of a risk assessment for an exotic species, risk managers are responsible for determining appropriate management actions. These should include both policy and operational measures. The Risk Assessment and Management Committee (1996) has suggested the key elements for risk management and operational requirements during and after the risk assessment (see Box 2). To evaluate the effectiveness of the implementation of risk management measures, the ecological risk assessments should be repeated on a regular basis to ensure that the risk of biological invasion remains low. Such repetition constitutes a form of sensitivity analysis to the initial risk assessment.

## ECOLOGICAL (PEST) RISK COMMUNICATION

It is essential that the draft and final risk assessment reports, and especially those generated from the qualitative approach, be reviewed by external experts who are not associated with the outcome of the assessment or with the risk assessors. The reviewers should be able to assess the quality of research and identify any problems, bias or misjudgement that may have arisen.

This risk communication process is extremely important for risk issues of high visibility in society. All documentations of the risk assessment should be made available

BOX 1

**Biological invasions: recommendations for United States policy and management**

**Facts:**
Invasions by harmful non-native increasing in number and area affected. The damages to ecosystems, economic activity and human welfare are accumulating. Without improved strategies based on recent scientific advances and increased investments to counter invasions, harm from invasive species is likely to accelerate.

**Way forwards:**
The Government is required to increase the effectiveness of prevention of invasions, detect and respond quickly to new potentially harmful invasions, control and slow the spread of existing invasions, and provide a national centre to ensure that these efforts are coordinated and cost effective.

**Recommended actions:**

(1) Use new information and practices to better manage commercial and other pathways to reduce the transport and release of potentially harmful species;
(2) Adopt more quantitative procedures for risk analysis and apply them to every species proposed for importation into the country;
(3) Use new cost-effective diagnostic technologies to increase active surveillance and sharing of information about invasive species so that responses to new invasions can be more rapid and effective;
(4) Create new legal authority and provide emergency funding to support rapid responses to emerging invasions;
(5) Provide funding and incentives for cost-effective programmes to slow the spread of existing invasive species in order to protect still uninvaded ecosystems, social and industrial infrastructure and human welfare; and
(6) Establish a National Centre for Invasive Species Management to coordinate and lead improvements in federal, state and international policies on invasive species.

*Source*: Lodge *et al.*, 2006.

BOX 2

**Elements of risk management and operational requirements**

**A. Elements to consider in risk management policy:**

- Risk assessments (including uncertainty and quality of data)
- Available mitigation safeguards (i.e. permits, industry standards, prohibition, inspection)
- Resource limitations (i.e. money, time, locating qualified experts, information needed)
- Public perceptions and perceived damage
- Social and political consequences
- Benefits and costs should be addressed in the analysis

**B. Risk management operational steps:**

*a.* ***Maintain communication and input from interested parties***: Participation of interested parties should be actively solicited as early as possible. All interested parties should be carefully identified because adding additional interested parties late in the assessment or management process can result in revisiting issues already examined and thought to have been brought to closure. They should be periodically brought up-to-date on relevant issues.

*b.* ***Maintain open communication between risk managers and risk assessors:*** Continuous open communication between the risk managers and the risk assessors is important throughout the writing of the risk assessment report. This is necessary to ensure that the assessment will be policy relevant when completed. Risk managers should be able to provide detailed questions about the issues that they will need to address to the risk assessors before the risk assessment is started. This will allow the assessors to focus the scientific information relevant to the questions or issues that the risk managers will need to address.

*c.* ***Match the available mitigation options with the identified risks:*** Matching the available mitigation options with the identified risks can sometimes be done by creating a mitigation plan for the organisms, or group of organisms. Where a specific organism or group of organism requires a specific mitigation process (e.g. brine dip of transfers for oysters), the efficacy for control should be recorded. Using this process it will become apparent which mitigation(s) would be needed to reduce the risk to an acceptable level.

*d.* ***Develop an achievable operational approach:*** Each new operational decision must consider a number of management, agency and biological factors that are unique to any specific organism or pathway. At an operational risk management level, each essential component in the operational sequence (risk assessment, current standard and policy, effective mitigation, feasibility and monitoring) should be examined before approval of the importation or release or action against an exotic organism or pathway is taken. These include the risk assessment, the development of conditions for entry to meet current industry or regulatory standards, effective mitigation of any identified potential exotic aquatic organisms, feasibility of achieving the mitigation requirements and finally, a system of monitoring to ensure that all mitigation requirements are maintained.

*Source*: Risk Assessment and Management Committee, 1996.

BOX 3
**Risk communication consideration for risk managers**

- Plan carefully and evaluate the success of your communication efforts.
- Coordinate and collaborate with other credible sources.
- Accept and involve the public as a legitimate partner.
- Listen to the public's specific concerns.
- Be honest, frank and open.
- Speak clearly and with compassion.
- Meet the needs of the media.

*Source*: USEPA, 1995

to the stakeholders (or interested parties), especially the aquaculture practitioners. The risk manager should allow feedback from the stakeholders and independent reviewers and respond to any comments. Original sources of supporting information in the risk assessment should be adequately documented for reviewers and stakeholders, and this may help to further identify information gaps (Risk Assessment and Management Committee, 1996). If there is disagreement on the results of a risk assessment (e.g. ratings in one or more of seven risk assessment elements) by the reviewers (or stakeholders), the reviewer or opponent party can point to the data used in determining that specific element-rating and show what information is missing, misleading or in need of further explanation. The Risk Assessment and Management Committee (1996) has stressed that focusing on information can help resolve disagreements and minimize the chances of preconceived outcome diluting the quality of the element-rating by the reviewers or interested parties.

To achieve effective and positive risk communication, the risk managers should clearly describe the sources and causes of the risks and potential impacts related to the proposed introduction. The degree of certainty in the risk assessment decision and the options for reducing the risks are also important and should be explained to interested parties (USEPA, 1995). Other important considerations for risk communication are shown in Box 3. In some cases, additional follow-up actions will be needed to address the comments made by the reviewers and/or stakeholders. Depending on the importance of the assessment, uncertainty in the risk assessment results and available resources (e.g. money and time), it may be worthwhile to conduct an additional iteration of the risk assessment with a view to refining the results and supporting a final management decision (USEPA, 1998).

## CONCLUSIONS

Given the ever-increasing global demand for and production of aquaculture products and the globalization of aquaculture industries, it is anticipated that imports of live aquatic organisms and thus the potential for introduction of exotic organisms will increase in the near future. Aquaculture-associated activities are important pathways for exotic introductions, some of which become invasive and nuisance species with significant ecological impacts and economic losses. Although some recent reviews indicated that the majority of introduced exotic species has done little ecological harm to native aquatic biodiversity (Escapa *et al*., 2004; De Silva *et al*., 2006; Soto *et al.,* 2007; FAO Database on Introductions of Aquatic Species), ecological risks from biological invasions as have occurred in Lake Victoria and Donghu Lake should not be ignored (Chen, 1989; Reinthal and King, 1997). Anthropogenically driven deterioration of environmental conditions in inland waters, drainage basins and coastal marine environments can make the conditions less congenial to native species and consequently favour exotic, robust species (De Silva *et al.,* 2006). Thus risk assessors should take both ongoing and projected environmental changes and the ecological risk of introducing exotic species into account.

The implementation of proper risk assessment schemes for screening the potential invasiveness of aquatic organisms before introduction will certainly reduce the risk of importing invasive species and thereby minimize ecological and economic impacts. The qualitative assessment methods described in this paper, which are easy to use and do not require large amounts of resources or expertise, can be readily adopted in Asia, which is the global centre of aquaculture production. The assessment method can be further developed and enhanced with advanced quantitative methods, if more relevant biological information on the taxonomic group of concern is available. As data and information availability has a huge influence on the quality and confidence of the risk assessment, it is essential to put more effort and funding into in basic research on the life histories, population dynamics and ecology of aquaculture organisms, and establish better regional and international biological invasion information systems for these species. Finally but most importantly, concerted efforts should be made to educate consumers and industries about the ecological risk and economic impacts of introducing invasive organisms, and to establish mandatory application of legally binding species-specific risk assessments and risk management that will reduce the risks of biological invasion through aquaculture activities.

## FUTURE CHALLENGES

With the growth of aquaculture industries, many farmers are attempting to culture new and profitable species. Among these new developments, many invertebrate species are now being introduced into aquaculture systems. The new culture organisms include various species of sea cucumbers, sea urchins and sea squirts. These new species may also be transported internationally with consequent risks of biological invasion. This certainly presents a real challenge to the current risk assessment and management practices that mainly deal with fishes, crustaceans and molluscs. More basic biological and ecological studies on these new farming species in relation to the predicted invasive sequence are needed.

Making risk assessment of biological invasion a legally binding procedure in aquaculture industries, especially in Asian countries, will remain the biggest and most difficult challenge. If this cannot be achieved, it is unlikely that voluntary risk assessment and management would be effective in preventing or controlling biological invasions. More efforts should be put into the development of economic instruments to give incentives to the aquaculture industry to follow the relevant codes of practice and risk assessment protocols.

Although better international network and surveillance systems for prevention and control of invasive aquatic organisms through aquaculture are needed, such tasks will require resources, adequate funding and coordination among countries in collating and updating relevant information and databases. These tasks are perhaps the greatest challenges.

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## ANNEX 1

### A list of examples of current international and regional treaties and agreements (obligatory and voluntary) for protection against invasive aquatic species[1]

| Instrument/institution | Relevant provisions/decisions/resolutions |
|---|---|
| Convention on Biological Diversity (Nairobi, 1992) http://www.biodiv.org | Article 8(h). Parties to "prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species". |
| United Nations Convention on the Law of the Sea (Montego Bay, 1982) http://www.un.org/Depts/los/index.htm | Article 196. States to take all measures necessary to prevent, reduce and control the intentional or accidental introduction of species, alien or new, to a particular part of the marine environment, which may cause significant and harmful changes. |
| The Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar, 1971) http://www.ramsar.org | COP7-Resolution VII.14 on Invasive Species and Wetlands |
| Convention on Migratory Species of Wild Animals (Bonn, 1979) http://www.cms.int/ | Range State Parties of Endangered Migratory Species (Annex 1) to prevent, reduce or control factors that are endangering or likely to further endanger the species, including exotic species. (Article III (4)(c)). Agreements for Annex II Migratory Species to provide for strict control of the introduction of, or control of already introduced exotic species detrimental to the migratory species (Article V (5)(e)). |
| Convention on the Law of Non-navigational Uses of International Watercourses (New York, 1997) http://www.un.org/ | Watercourse States shall take all necessary measures to prevent the introduction of species, alien or new, into an international watercourse. (Article 22). |
| International Plant Protection Convention (Rome, 1951, as amended in 1997) https://www.ippc.int/IPP/En/default.jsp | Creates an international regime to prevent spread and introduction of plants and plant products through the use of sanitary and phytosanitary measures by Contracting Parties. Parties establish national plant protection organizations and agree to cooperate on information exchange and on the development of International Standards for Phytosanitary Measures. Regional agreements for Europe and the Mediterranean, the Asia-Pacific, Near East, Pacific, Caribbean, North America, South America and Africa. |
| Plant Protection Agreement for the Asia and Pacific Region (Rome, 1956) https://www.ippc.int/IPP/En/default.jsp | Contracting governments to prevent the introduction into and spread within the South East Asia and Pacific Region of plant diseases and pests. A supplementary agreement under Article III of the IPPC. |
| IUCN-Guidelines for the Prevention of Biodiversity Loss Caused by Invasive Alien Species (2000) http://www.iucn.org/ | Guidelines designed to increase awareness and understanding of the impact of alien species. Provides guidance for the prevention of introduction, re-introduction, and control and eradication of invasive alien species. |
| Guidelines for the Control and Management of ships' Ballast Water to Minimize the Transfer of Harmful Aquatic Organisms and Pathogens. (Resolution A.868 (29)1997, International Maritime Organisation) http://www.imo.org | Provides guidance and strategies to minimize the risk of unwanted organisms and pathogens from ballast water and sediment discharge. Revokes the "Guidelines for Preventing the Introduction of Unwanted Organisms and Pathogens from Ships' Ballast Water and Sediment Discharges" (IMO Resolution A. 774 (18) 1991). |
| Agenda 21-United Nations Conference on Environment and Development (Rio, 1992) http://www.un.org/esa/sustdev/documents/agenda21/index.htm | Calls for increasing protection of forests from disease and uncontrolled introduction of exotic plant and animal species (11.14); acknowledgement that inappropriate introduction of foreign plants and animals has contributed to biodiversity loss (15.3); appropriate rules on ballast water discharge to prevent spread of non-indigenous organisms. 17.30(vi); controlling noxious aquatic species that may destroy other aquatic species (chap. 18-40(e)(iv)). |
| Code of Practice on the Introductions and Transfers of Marine Organisms (ICES/EIFAC 2004) http://www.ices.dk/reports/general/2004/ICESCOP2004.pdf | Recommends practices and procedures to diminish risks of detrimental effects from marine organism introduction and transfer, including those genetically modified. Requires ICES members to submit a prospectus to regulators, including a detailed analysis of potential environmental impacts to the aquatic ecosystem. |
| Code of Conduct for Responsible Fisheries (FAO 1995) http://www.fao.org/fi/agreem/codecond/ficonde.asp | Encourages legal and administrative frameworks to facilitate responsible aquaculture. Including pre-introduction discussion with neighbouring states when non-indigenous stocks are to be introduced into transboundary aquatic ecosystems. Harmful effects of non-indigenous and genetically altered stocks to be minimized especially where significant potential exists for spread into other states or country of origin. Adverse genetic and disease effects to wild stock from genetic improvement and non-indigenous species to be minimized. |

## ANNEX 1 (continued)

| Instrument/institution | Relevant provisions/decisions/resolutions |
|---|---|
| Code of Conduct for the Import and Release of Exotic Biological Control Agents (FAO 1995) http://www.fao.org | Aims to facilitate the safe import, export and release of such agents by introducing procedures of an internationally acceptable level for all public and private entities involved, particularly where national legislation to regulate their use does not exist or is inadequate. Outlines specific responsibilities for authorities of an exporting country, who should ensure that relevant regulations of the importing country are followed in exports of biological control agents. |
| Preventing the Introduction of Invasive Alien Species. Resolution A-32-9, International Civil Aviation Organisation (ICAO) (1998) http://www.icao.int/ | Urges all Contracting States to use their civil aviation authorities to assist in reducing the risk of introducing, through civil air transportation, potentially invasive species to areas outside their natural range. Requests the ICAO Council to work with other United Nations organizations to identify approaches that the ICAO might take in assisting to reduce the risk of introducing potential invasive species. |
| Global Programme of Action for the Protection of the Marine Environment from Land-based Activities (UNEP 1995) http://www.gpa.unep.org/ | Introduction of alien species acknowledged as having serious effects upon ecosystem integrity. |

[1] *Source*: http://www.chinabiodiversity.com/etf/appendix3-en.htm

## ANNEX 2
## Organism risk assessment form

(Modified from the generic non-indigenous aquatic organisms risk analysis review process, report to the aquatic nuisance species tasks force 1996)

File No.: ________________________________________

Date: ___________________________________________

Organism (Scientific and common names): ____________________________________

Analyst(s): _______________________________________________________________

Pathway: _________________________________________________________________

Origin of the Organism: ____________________________________________________

1. Literature review and background information (summary of life history such as growth rate, egg size, diet breadth, reproduction strategy etc., distribution, tolerable rages of temperature and salinity, and invasion history if any; include references):

2. Pathway Information (include references):

3. Rating elements for the PIES·COM model: Rate statements as L: Low, M: Medium, or H: High. Place specific biological information in descending order of risk with reference(s) under each element that relates to your estimation of probability or impact. Cite the literature (i.e. author, year) or use the reference codes of the biological statement (G: General knowledge, J: Judgment evaluation and E: Extrapolation) where appropriate and the uncertainty codes (VC: Very certain, RC: Reasonably certain, MC: Moderately certain, RU: Reasonably uncertain and VC: Very uncertain) after each element rating.

3.1. Probability of Establishment

| Risk Element | Element Rating (L, M, H) | Uncertainty Code (VC, RC, MC, RU, VU) | Reference Codes |
|---|---|---|---|
| Pathway risk | | | |
| Introduction risk | | | |
| Establishment risk | | | |
| Spreading risk | | | |

3.2. Consequence of Establishment

| Impact Element | Element Rating (L, M, H) | Uncertainty Code (VC, RC, MC, RU, VU) | Reference Codes |
|---|---|---|---|
| Ecological impact | | | |
| Perceived impact | | | |
| Economic impact | | | |

4. Risk Characterization

4.1. Determination of a combined rating for the probability of establishment (PE) by taking the lowest rating among the four elements.

| | Pathway | Introduction | Establishment | Spreading |
|---|---|---|---|---|
| Risk Rating (L, M, H) | | | | |
| PE Score (L, M, H) = | | | | |

4.2. Determination of a combined rating for the probability of the consequence of establishment (CE Score) by matching one of the listed scenarios with the current study.

| Scenario | Ecological | Economic | Perceived | CE Score |
|---|---|---|---|---|
| Impact Rating for this study (L, M, H) | | | | |
| 1 | H | L,M,H | L,M,H | H |
| 2 | L,M,H | H | L,M,H | H |
| 3 | M | M | L,M,H | M |
| 4 | M | L | L,M,H | M |
| 5 | L | M | L,M,H | M |
| 6 | L | L | M,H | M |
| 7 | L | L | L | L |

4.3. Determination of the final rating of organisms risk potential (ORP) by putting the values of PE and CE determined from 4.1 and 4.2, and matching with one of the listed cases with this study. ORP Rating (L, M, H) = ____________________________

| Case | Probability of Establishment | Consequence of Establishment | OPR Rating |
|---|---|---|---|
| Rating for this study (L, M, H) | | | |
| 1 | High | High | = High |
| 2 | Medium | High | = High |
| 3 | Low | High | = Medium |
| 4 | High | Medium | = High |
| 5 | Medium | Medium | = Medium |
| 6 | Low | Medium | = Medium |
| 7 | High | Low | = Medium |
| 8 | Medium | Low | = Medium |
| 9 | Low | Low | = Low |

4.4. Determination of the pathway risk potential (PRP) based on the rating distribution of the seven elements used for deriving the organism risk potential (ORP), by matching one of the following listed scenarios. PRP Rating (L, M, H) = ____________________

| Characteristics of the Rating Distribution of the Seven Elements for Deriving ORP | PRP Rating |
|---|---|
| 1 or more scored with High rating(s) out of the seven | High |
| 5* or more scored with Medium rating(s) out of the seven | High |
| 1–5* scored with Medium rating(s) out of the seven | Medium |
| All scored with Low ratings | Low |

*Note: The number, 5 used in this table is arbitrary. The selection of value 4 or 5 is possible when the number of Medium risk organisms reaches a level at which the total risk of the pathway becomes high.

4.5. Recommendations on the proposed introduction and mitigation measures based on the definition given below.

| **Rating of ORP or PRP** | **Definition** | **Actions** |
|---|---|---|
| Low | Acceptable risk: organism(s) of little concern | • Introduction may be permitted<br>• No mitigation is required |
| Medium | Unacceptable: organism(s) of moderate concern | • Introduction should be banned or should be controlled via risk management<br>• Mitigation is justified |
| High | Unacceptable: organism(s) of high concern | • Introduction should be banned<br>• Mitigation is justified |

Recommendations: ____________________________________________________
______________________________________________________________________
______________________________________________________________________

5. Specific Management Questions: ______________________________

6. Remarks: ______________________________

7. Cited References: ______________________________

– End of the Organism Risk Assessment –

## ANNEX 3

**Recent studies applying quantitative risk assessment models for predicting and assessing the invasiveness of aquatic organisms**

| Species or taxonomic group of concern | Region of study | Reference |
|---|---|---|
| Molluscs | San Francisco Bay, USA | **Miller, A.W., Ruiz, G.M., Minton, M.S. & Ambrose, R.F.** 2007. Differentiating successful and failed molluscan invaders in estuarine ecosystems. *Mar. Ecol. Progr. Ser.,* 332: 41–51. |
| Green crab (*Carcinus maenas)* | Washington, USA | **Colnar, A.M. & Landis W.G.** 2007. Conceptual model development for invasive species and a regional risk assessment case study: the European green crab, *Carcinus maenas*, at Cherry Point, Washington, USA. *Hum. Ecol. Risk Assess.,* 13: 120–155. |
| Molluscs | Laurentian Great Lakes | **Keller, R.P., Drake, J.M. & Lodge, D.M.** 2007. Fecundity as a basis for risk assessment of nonindigenous freshwater molluscs. *Cons. Biol.,* 21: 191–200. |
| Fishes (Cyprinidae) | USA | **Chen, P.F., Wiley, E.O. & Mcnyset, K.M.** 2007. Ecological niche modeling as a predictive tool: silver and bighead carps in North America. *Biol. Invas.,* 9: 43–51. |
| Fishes | Europe and North America | **Jeschke, J.M. & Strayer, D.L.** 2006. Determinants of vertebrate invasion success in Europe and North America. *Global Change Biol.,* 12: 1608–1619. |
| Fishes | California, USA | **Moyle, P.B. & Marchetti, M.P.** 2006. Predicting invasion success: freshwater fishes in California as a model. *Bioscience*, 56: 515–524. |
| Fishes | Colorado River, USA | **Olden, J.D., Poff, N.L. & Bestgen, K.R.** 2006. Life-history strategies predict fish invasions and extirpations in the Colorado River Basin. *Ecol. Monogr.,* 76: 25–40. |
| Fouling organisms | New Zealand | **Floerl, O., Inglis, G.J. & Hayden B.J**. 2005. A risk-based predictive tool to prevent accidental introductions of nonindigenous marine species. *Env. Manag.,* 35: 765–778. |
| Fishes | Laurentian Great Lakes, Canada | **Rixon, C.A.M., Duggan, I.C., Bergeron, N.M.N., Ricciardi, A. & Macisaac, H.J.** 2005. Invasion risks posed by the aquarium trade and live fish markets on the Laurentian Great Lakes. *Biodiversity Cons*., 14: 1365–1381. |
| Fishes | California, USA | **Marchetti, M.P., Moyle, P.B. & Levine, R.** 2004. Alien fishes in California watersheds: characteristics of successful and failed invaders. *Ecol. Appl.,* 14: 587–596. |

## ANNEX 4

### Regulations of aquaculture escapes in 2003[1]

| Country | Facility design | Prevention and response plans | Monitoring and enforcement |
|---|---|---|---|
| United States (Maine) | Each aquaculture facility must employ a containment management system to prevent the escape of fish. Starting in May 2004, all Atlantic salmon placed in net pens must be of North American origin. The use of transgenic fish is prohibited. Timeline established for marking all new fish placed in net pens to identify the facility owner and confirm that the fish are from Maine. | Each facility must report known or suspected escapes of more than 50 fish with an average weight of at least 2kg each within 24 hours. | Certain agencies are authorized to inspect aquaculture facilities for compliance with general permit. Each containment management system will be audited at least once per year and within 30 days of a reportable escape. |
| United States (Washington) | All marine finfish hatched after 31 December 2003 must be marked so that they are individually identifiable to the aquatic farmer. The use of transgenic fish is prohibited. | Aquaculture facilities must have an escape prevention plan and an escape reporting and recapture plan. | Aquaculture facilities must have procedures for monitoring the implementation of the escape prevention plan. Employees of the Washington Department of Fish and Wildlife are authorized to conduct inspections at the aquaculture facilities. |
| Canada (British Columbia) | Regulations exist for construction, installation, inspection, and maintenance including comprehensive regulations for net cages and related structures. | Aquaculture facilities must have written escape response plans. Facilities must verbally report any escapes within 24 hours of the discovery of an escape or evidence suggestion an escape. | Inspectors are authorized to investigate facilities' compliance with aquaculture regulations. No requirement for monitoring by license holder. Monitoring only via Atlantic Salmon Watch reporting system. |
| Canada (New Brunswick) | No escape regulations exist. | No escape regulations exist. | No escape regulations exist. |
| Chile | No escape regulations exist. | No escape regulations exist. | No escape regulations exist. |
| Faroe Island | No escape regulations exist. | No escape regulations exist. | No escape regulations exist. |
| Iceland | No specific requirements, but escape prevention is a general condition of aquaculture operating licenses. | Aquaculture operating licenses must specify plans to catch escaped fish. Escaped fish must be reported immediately. | Compliance with regulations is monitored twice annually. Failure to comply with regulations can result in loss of operator license. No system of public reporting on compliance. |
| Ireland | No specific requirements, but escape prevention is a general condition of aquaculture operating licenses. | Facility owners must immediately report fish escapes and have contingency plans for fish escapes. | No systematic collection of data on contingency plans for fish escapes or plans for escape prevention. On-site audits of wear or fatigue on key elements of aquaculture system. |
| Norway | No specific requirements for escape prevention, although regulations are under development. Farms are required to have nets in the sea around each site in winter for monitoring escaped farm fish. | Aquaculture facilities must keep contingency plans for limiting the size of escapes and recovering escaped fish. Escapes must be reported immediately. | Government operates "national program of action against escapes" and examines contingency plans and recorded keeping on operational procedures. |
| Scotland | For existing sites, a voluntary code of practice for stock containment addresses the design and construction of aquaculture equipment and procedures that could affect escapes. New sites must have escape prevention plans. | For existing sites, a voluntary code of practice requires contingency plans for recapturing escaped fish. New sites must have contingency plans. | No evidence of government monitoring of escape prevention procedures or of contingency plans for escapes. |
| Tasmania | No escape regulations exist. | The holder of a marine farming license must take reasonable precautions to prevent the release, deposit or escape into state waters of any introduced fish. | No escape regulations exist. |

[1] From Naylor *et al.*, 2005.