Ecological Risk Assessment of Marine Fish Aquaculture

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Introduction

The Environment and the Intervention of Marine Aquaculture

Few, if any, human interventions in the environment fail to have impact. In some cases interventions are potentially so damaging that they must be eliminated. On the other hand, the majority of human interventions are purposeful and designed to be of benefit to humans, so it is necessary that they proceed responsibly, sharing equitably in the use of nature's vital resources. It is thus important that these interventions are carefully managed with good stewardship to ensure that benefits can be achieved over time frames of many decades.

Aquaculture, together with fisheries and agriculture, has long been a provider of food for human consumption. For over three millennia it has been a necessary and often the only source of animal protein for pastoral communities living at subsistence levels. But within the last century its history has dramatically changed, and science and technology have propelled modern aquaculture into semi-intensive and intensive farming systems. These systems have greatly increased its degree of exposure to the environment. Consequently, although aquaculture remains a crucial cornerstone of rural life in many countries, its modern practices and array of commercial end-products are, to the rest of the world, dependent more on human life style decisions governed by social choice.

Fortunately, an important factor in social choice as aquaculture emerges in the twenty-first century is not only to minimize the impact of all human interventions on the environment but also to sustain the existing integrity of its many ecosystems in perpetuity. This has become a challenge to all resource-based industries, not only marine aquaculture. There are innumerable aquatic ecosystems in which aquaculture intervention is feasible. Each and every ecosystem has its own very specific and desired values, and therefore for the stewards of these resources to set specific goals around these values it is necessary for them to know in advance 1) what integrity means for each ecosystem and what specifically needs to be protected; and 2) which ecological resources and processes have to be sustained and for what reason. Compared with that of terrestrial ecosystems, comprehensive knowledge of aquatic ecosystems is severely constrained. Partly this is because much of the ecosystem lies below water and is thus not readily observable, but also the need for extensive

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environmental research of marine ecosystems is only now becoming recognized in many countries.

Many aquatic and terrestrial ecosystems can be said to be equally fragile, but the factors differ as do the mechanisms available for remediation. Most human interventions in aquatic ecosystems, such as mineral extraction, fishing, and now aquaculture, may induce more lasting far-field effects unless properly managed. Nonetheless, these and any other industries that integrate with open waters, such as tourism and recreational boating, all have a right to exist equitably as stakeholders; the effects on the aquatic ecosystem by one should not eliminate the existence of another.

In enabling aquaculture to share aquatic resources responsibly, the stewards of these resources are faced with many options. Invariably these options cannot be quantified adequately, and thus managers must estimate their potential ecological risks through individual risk assessments. Nonetheless, although ecological risks are a paramount concern, the final decision is frequently decided by other factors brought to bear by social choice, such as economic benefits to a local community, or issues of public health.

Using the Guidelines Document

Before any decisions can be made with regard to the siting or operation of a marine aquaculture facility, the first responsibility of risk managers, and that includes both managers of resources as well as managers of aquaculture operations, is to draw their conclusions from all information provided by the risk assessors that a perceived risk to a particular ecosystem has validity or not, and if so to estimate its degree of adverse effect. This may or may not be a straightforward task. In some cases the information reported to them by the risk assessors may be an excellent combination of field and laboratory data to compare with recognized benchmarks of stress, while in others it may be no more than the long-time experience of practitioners.

Irrespective of the final detail, it is important that the information is considered, collected, analyzed, characterized, and reported in a structured fashion. This ensures that the risk assessment report is not only complete as far as it can be (Table 1), but also that it can be compared directly with similar risk assessments made by other individuals elsewhere.

These guidelines for the risk assessment of marine fish aquaculture attempt to facilitate the

Table 1. Possible contents of a risk assessment report.

- Description of the preliminary objectives and plans
- Description of the environmental setting for the planned development
- Description of the proposed aquaculture practice and species to be cultured
- Review of the conceptual model and the assessment end points
- Discussion of the major data sources and analytical procedures used
- Review of the stressor response and exposure profiles
- Description of the risk to the assessment end points, including risk estimates and adversity evaluations
- Review and summary of major areas of uncertainty, and their direction, and approaches used to address them, such as:
    - Discussion of the degree of scientific consensus in key areas of uncertainty
    - Identification of major gaps and, where appropriate, indicate whether gathering additional data would add significantly to the overall confidence in the assessment results
    - Estimation of the risk probability by combining numerical data
    - Discussion of science policy judgments or default assumptions used to bridge information gaps and the basis for the assumptions
    - Discussion of how elements of quantitative uncertainty analysis are embedded in the estimate of risk

work of risk assessors and risk managers to achieve these objectives. In brief, the guidelines:

- identify the 10 areas of substantive risk in the interaction between marine fish aquaculture operations and the environment;
- identify the biological end points or entities and their attributes, both locally and far field, that might be affected in those areas of risk;
- identify methodologies for measuring or monitoring the effects of exposure to each area of risk;
- provide a common framework, or step-by-step process, to estimate the degree of potential adversity of each area of risk, together with its mitigation; and
- provide a concept of the physical and environmental demands of marine fish aquaculture sites, and a matrix to suggest different orders of relevance for the application of each area of risk in different global ecosystems.

In planning a risk assessment, it is recommended that the risk managers and risk assessors, together with others with experience in marine fish aquaculture, first review the areas of risk identified as priorities in the guidelines, and establish their relevance in their own geographic region and to the particular local ecosystem where marine aquaculture facilities are to be sited. It is very probable that not all areas of risk will be applicable to every development site, and therefore a matrix has been developed as part of the guidelines to suggest some of the more common differences (see "Near-field and Far-field Effects"). For those that are important, the respective templates (as described in Appendices A-J of the full document) can be used.

Ecological Risk Assessment of Marine Fish Aquaculture

Framework

For more than 20 years, countries have been developing national guidelines for environmental risk assessment. At first their focus was predominantly on environmental risks to a single species (humans) and one end point (human health), but later nonhuman-oriented environmental risk assessments were included. These not only considered the risk to entire communities and addressed any number of selected end points, but they also included the possible effects of nonchemical stressors.

In order to accommodate the sudden burst of different views and approaches to environmental risk assessment by its member countries, the United Nations (UN) World Health Organization (WHO) developed a common analytical framework. The WHO Framework is adopted here for developing Guidelines for Ecological Risk Assessment of Marine Fish Aquaculture (this technical memorandum) because it provides a generic analytical framework that has been widely reviewed and accepted by international experts in UN-sponsored workshops.

The WHO Framework (Figure 1) represents the scope of the guidelines for undertaking ecological risk assessments. It represents a three-dimensional figure, with planes surrounding the actual risk assessment to depict the total process. These planes represent the continuum for all those who are involved in the decision-making process, and includes not only the interactions between risk managers and risk assessors (the scientific and technical experts), but also their interaction with stakeholders who may be affected by any decision. For marine aquaculture, participating stakeholders are typically the fish farmers and their trade associations, waterfront property owners, recreational users of waters, other fishing and aquaculture bodies, and environmental advocacy groups. The extent of stakeholder interaction, and at what point it is considered in the decision-making process, is the prerogative of the decision-maker, and varies from one country to another in accordance to the regulatory, legal, and decision-making climate. Furthermore, stakeholders might perform their own risk assessments with or without the help of technical consultants, with differences arguable in court.

The risk assessment process is itself divided into three segments. These segments represent three distinct phases of work, but once again there is a continuum of interplay between the persons

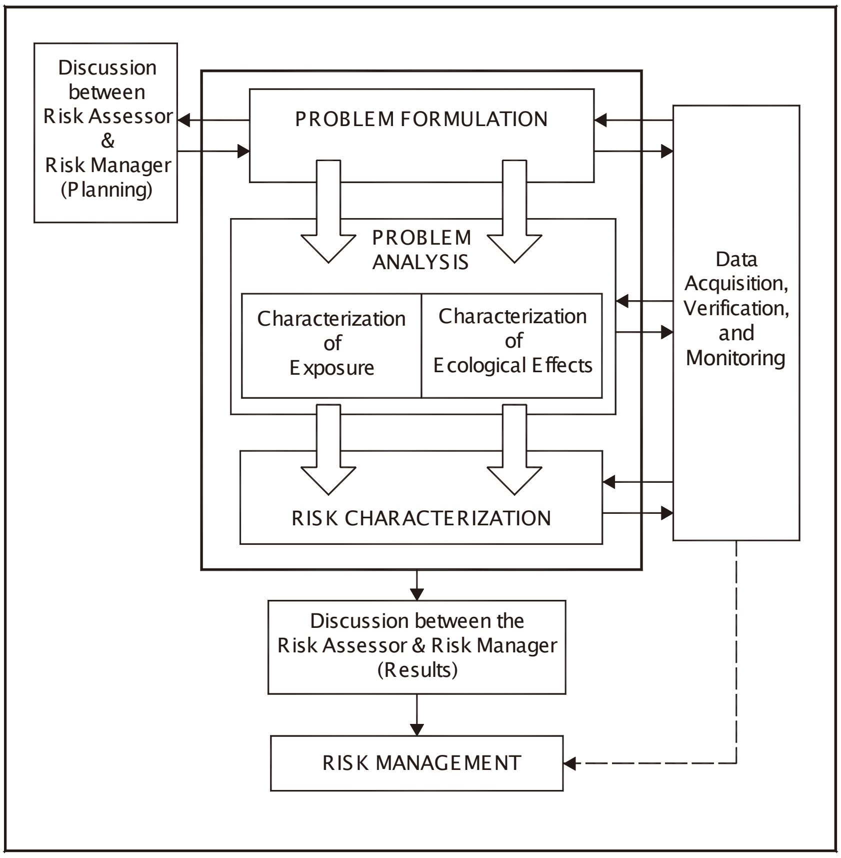

Fig. 1. The WHO framework for ecological risk assessment.

involved.

The following sections describe in broad terms a generic risk assessment process but without direct application to any specific category of risk. Detailed processes can be found for all the principal categories of risk from marine fish aquaculture in Appendices A-J of the full document.

Problem Formulation for Marine Fish Aquaculture (Phase 1)

The first phase is problem formulation, or the identification of key factors to be considered in the risk assessment. Here all the necessary plans are made by the risk managers and risk assessors to determine how the analysis will be performed. These include, for example:

- the scope, focus, and sources to be considered (such as the type of marine aquaculture, and species);
- the biological or ecological end points and their attributes that are the concern for protection (such as sea grass preservation, maintenance of water quality, avoidance of low dissolved oxygen, avoidance of eutrophication, etc.);
- a conceptual model or diagram of how the system being assessed is thought to be organized; and finally,
- the plan for analyzing the information and conducting the rest of the assessment.

Problem formulation can be a long and difficult process. It depends on the degree of familiarity with the particular field of aquaculture, how contentious are any issues, and finally who is involved. Unfamiliar problems, such as the location of marine fish cages in the migratory routes or breeding grounds of cetaceans, unquestionably take longer to formulate compared with, say, the location of a land-based marine fish hatchery adjacent to an existing recreational marina or fish processing plant.

Modern marine fish aquaculture has been evolving for almost 50 years. Consequently, considerable experience has been building with regard to any real or perceived impact on marine ecosystems all over the world. Most of the practical knowledge and experience by fish farmers themselves has never been recorded, although some has been documented in gray literature, but a considerable volume of scientific and technical research can now be found in peer-reviewed journals. With this growing background information to draw on, it is possible for risk managers and risk assessors to undertake a very comprehensive problem formulation.

For the purpose of these guidelines the possible observed or perceived effects of marine aquaculture have been summarized in 10 categories (Table 2). Within these broad designations it is not possible to include all the possible effects which might be identifiable globally, and consequently the guidelines concentrate on the sources of effects, and the end points or entities of concern together with their attributes, of known importance to the majority of marine ecosystems. A risk assessment can include any number of other effects, but practical experience suggests that the 10 categories and their contents illustrated here provide a strong starting point. The biological end points of these possible effects are generalized in the following paragraph.

Biological end points of marine fish aquaculture and their attributes can be described in collective terms (such as the species abundance of the infauna), or very specifically by location (such as the discovery of giant tubeworms at hydrothermal vents). They may also be assessed generally (such as by the presence of certain species in the epifauna), or by specific measurements (such as by n, μg/g, or μg/L).

The end points identified in these guidelines for protection from marine fish aquaculture activities may include:

- the species richness and abundance of the seston, nekton, or infauna,
- the abundance of a specific species in the seston, nekton, or infauna,
- the species richness and abundance of the epifauna,
- the abundance of a specific species in the epifauna,
- the abundance of a specific species of marine mammal, reptile, or bird,
- the immune resistance of demersal and pelagic fishes,
- the number and fitness of the natural (conspecific) population,
- the fitness of another fish population, and
- the abundance of the industrial fisheries.

The choice of species may be guided by whether one is looking for a surrogate for system stressors, system response, or protection of some desirable biological attribute. Thus, one might measure a toxic phytoplankton species because of the desire to avoid blooms of harmful or nuisance species, or one might choose a species that is indicative of degraded environmental condition (e.g., capitellid worms or the presence of *Beggiatoa* spp. in sediments), or one might measure sea grass distribution because of its high protection status.

Problem Analysis for Marine Fish Aquaculture (Phase 2)

Problem analysis is the second phase of risk assessment when all available scientific information relevant to the issue is collected and applied. For the most part it is carried out by technical experts. Problem analysis is divided into two parts. The first is the analysis of exposure, which predicts or measures the spatial and temporal distribution of a stressor and a point of concern; the second is the analysis of effects (sometimes called the exposure response), which identifies and quantifies any adverse effects caused by a stressor.

Characterizing the Background of an Aquaculture Site

It is important to know the characterization of the marine site(s) where the stressor originates and where it may have its adverse effects. Therefore the first step is a baseline survey, or stock-taking, of information about the near field, and in some cases the far field. The survey is in two parts, namely, collecting information through a literature search followed by assembling current information and data by field work.

Historical information

A valuable part of the baseline survey is a

Table 2. Categorization of observed or perceived effects associated with marine fish aquaculture, and the identifiable sources of the stressor.

Effects	Sources
1. Increased organic loading	• Particulate organic loading o Fish fecal material o Uneaten fish feed o Debris from biofouling organisms o Decomposed fish mortalities on the farm • Soluble organic loading o Dissolved components of uneaten feed o Harvest wastes (blood)
2. Increased inorganic loading	• Nitrogen and phosphorus from fish excretory products • Trace elements and micronutrients (e.g., vitamins) in fish fecal matter and uneaten feed
3. Residual heavy metals	• Zinc compounds in fish fecal material • Zinc compounds in uneaten feed • Copper compounds in antifouling treatments
4. The transmission of disease organisms	• Indigenous parasites and pathogens • Exotic parasites and pathogens
5. Residual therapeutants	• Treatment by inoculation • Treatment in feed • Treatment in baths
6. Biological interaction of escapes with wild populations	• Unplanned release of farmed fish • Unplanned release of gametes and fertile eggs • Cross infection of parasites and pathogens • Planned release of cultured fish for enhancement or ranching
7. Physical interaction with marine wildlife	• Entanglement with lost nets and other jetsam • Entanglement with nets in place, structures, and moorings, etc. • Attraction of wildlife species (fish, birds, marine mammals, reptiles) • Predator control
8. Physical impact on marine habitat	• Buoyant fish containment structures and mooring lines • Anchors and moorings
9. Using wild juveniles for grow-out	• Harvest of target and nontarget species as larvae, juveniles, and subadults
10. Harvesting industrial fisheries for fish feed	• Increased fishing pressure on the shoaling small pelagic fish populations

search of existing literature of water and sediment quality parameters. These include, for example, data on water temperatures, salinity, dissolved oxygen, stratification, bottom currents, water depth, background nutrient concentrations, phytoplankton species and chlorophyll, sediment grain size, and organic matter content. In those cases where information is not available, then a program of data collection should be initiated to fill the gaps. It is hard to be prescriptive about spatial and temporal scales of measurement, but measurement of some water quality parameters may need to be taken on a weekly basis during seasons of high phytoplankton productivity.

Some additional information might be available on the background levels of contaminants in both the water and in the sediments. These include, for example, metals, and organics such as hydrocarbons, pesticides, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs), etc. This information is particularly important (and more likely to be available) in near-shore coastal areas where there are significant anthropogenic inputs from agricultural and urban areas. In open waters there is little potential for the accumulation or discharge of these types of contaminants, and the need is reduced.

Finally, any documentation providing a broad description of the natural history of the area, together with any reports or local knowledge of the potential for noxious phytoplankton blooms or the prevalence and intensity of known parasites are potentially useful. Information on the incidence of blooms and parasites is more likely if there are commercial shellfish resources in the area.

Current information

A typical baseline survey of current information for the lease area will include most of the items from the following checklist:

1. Identification of sensitive habitats. These may include, for example, beds of macroalgae and eelgrass, coral reefs, commercially valuable shellfish beds, spawning grounds and breeding areas, migratory pathways of aquatic species, rocky reef communities, and all other structures valuable as nurseries. Such habitats within 500 m of a proposed intensive farm site should be mapped, with the intention of avoiding them whenever possible.
2. The background physico-chemistry of the sediments. This may include, for example, total volatile solids (TVS) or organic matter content, redox potential (Eh), sediment grain size (SGS), free sulfide ($S^{=}$), and the two inorganic metals copper and zinc.
3. An inventory of the species and abundance of the macrobenthic communities. This may be carried out by stratification, or by the type of habitat.
4. The hydrographic variables, such as currents, tides and residence times, including acoustic doppler current profiler (ADCP) data collected over at least one lunar cycle, and bathymetry within 500 m of the proposed site.
5. A profile of water quality, including temperature, salinity, and the potential for stratification as a function of season (pycnoclines and haloclines).
6. A profile of primary productivity, including major species (including any toxic species), chlorophyll (Chl_a), phaeophytin, and dissolved oxygen (DO).
7. If possible, underwater surveys recorded on a video or a series of photographs to provide an overall, semiquantitative assessment of the benthic environment of the site, especially in deep water.
8. Finally, identification of activities by other resource users, such as marine sanctuaries, marine protected areas, fishing grounds, recreational areas, navigational channels, oil and mineral extraction, military training areas, and approved dumping grounds, etc.

The grid on which this information for the baseline survey is to be collected depends on the homogeneity of the system. A regression approach is recommended with single samples collected at intervals on four orthogonal transects beginning at the center of the proposed farm location. Samples should extend at least 500 m from the center. If video surveys are conducted first, the grab collections can be focused in areas where samples are possible, namely soft to mixed substrates. About 24 samples are adequate.

The profile of the macrobenthic community can be reduced in cost by using the smaller petite ponar grab (with a 0.0225 m^2 footprint) rather than the more standard van Veen grab (0.1 m^2).

Near-field and Far-field Effects

Effects of aquaculture interventions on the ecosystem are spatial and temporal. They can be localized and immediate, or distant and sometime in the future. However, both near-field and far-field effects have to be considered in the risk assessment process.

Near-field effects

The near field can be defined as that area encompassing the limit of directly measurable effects. In the marine environment, the majority of human interventions, such as sand mining, dredging, drilling, waste disposal, fish processing, and recreational boating, etc., all have instant near-field effects, particularly on the sediments and their benthic communities in the immediate vicinity of the source. Consequently, because of the long history of these activities in marine waters, the extent and diversity of their effects are well known. They can be measured with accuracy, and the particulate data and benthic biological data linked in a number of empirical or mechanistic models to assess potential risk.

With regard to the relatively recent intervention of aquaculture in the marine environment, and its most localized and instant impact of wastes and contaminants accumulating on the bottom sediment beneath fish enclosures or in solution, there is a wealth of comparative information about the measurement of near-field effects on which to draw. For example: 1) in terms of sedimented organic waste, the near field describes that area in which statistically significant differences (t-tests, ANOVA, etc.) or significant clines (statistically significant coefficients on dependent variables in linear or nonlinear regression analysis) in either physico-chemical or biological end points associated with aquaculture-related effects can be demonstrated at the peak of farm production; and 2) in terms of reduced concentrations of dissolved contaminants or effects of metabolic waste, the near field describes that area in which statistically significant increases or decreases in the end point of interest can be measured in comparison with local reference conditions.

Because of the extent of good data, near-field effects are generally assessed using local computer models to predict the deposition of organic material released by the producer. The DEPOMOD computer modeling tool, for example, models benthic enrichment effects by combining particle tracking with empirical relationships between the spatial distribution of solids and changes in the structure of the benthic community.

Near-field effects are usually limited or managed by regulatory authorities setting performance standards, which are appropriate for the location or the region as a whole. Typically, under the terms of a permit or license, the producer is responsible for conducting the necessary monitoring and complying with the management practices adopted to enable the performance standards to be met.

Far-field effects

Far-field effects are those effects that occur outside that area where statistically significant clines in relationship with the source cannot be measured. These are cumulative effects that normally can only be detected by long-term monitoring programs at locations not directly influenced by local effects. Assessment of far-field effects associated with aquaculture becomes increasingly important as the industry expands.

The maximum spatial extent of far-field effects is a hydrologic unit that includes all inputs potentially affecting the unit. It may include, for example, a single bay, several bays, or an entire estuary or delta. Far-field effects become increasingly difficult to measure in open bodies of water, such as those offshore where aquaculture may occur. However, even in large open bodies of water the same definitions could be applied.

Because of the vast scope of far-field effects, their potential is normally best assessed through computer models. These are monitored by consortiums of contributors to the cumulative effects in coordination with some level of government. Management of far-field effects is normally a public function in cooperation with all the contributors. With regard to organic loading, for example, from a number of marine fish farms into a bay 10 km distant, the regulatory authority may set Total Maximum Daily Loads (TDML) for the far field of interest (the bay), and apportion the TMDL to individual producers or farm complexes. The authority then manages the far-field effects by manipulating the respective TMDLs to meet one stated objective.

Risk Characterization for Marine Fish Aquaculture (Phase 3)

Risk characterization is the final phase when the two analyses of exposure and effects are brought together. It is best performed using models developed to estimate effects from hypothetical risks.

In a number of fields, such as the pharmaceutical industry or chemical engineering, risk characterization can be straightforward. The point estimate of exposure is compared with the point estimate of the threshold of effects, and if the ratio is greater than one then an effect is assumed. It can be taken further with an exposure-response model, when the distribution of the exposure and effects can be shown to accumulate over a period of time. However, in the marine aquaculture industry the process of risk characterization is complicated by the fact that most of the effects are interactive. Such complexity could be dealt with by modeling, but quantifiable information for many aspects of marine aquaculture is extremely scarce. Consequently, for risk characterization the only recourse at present is either to make use of a mechanistic model for a particular site, providing the assumptions are reasonable and that the model can be adequately calibrated and validated, or to rely on all existing information and especially the classical "dose and response" laboratory information.

In assessing a risk it is important both to qualify and quantify, where possible, the associated uncertainty. For example, the uncertainty could be described by probabilistic factors, by semiquantitative factors, or entirely qualitative factors, such as high, medium, or low. Whatever factors are chosen, it is important to include the uncertainty with any risk assessment. In addition, it is important to explain any assumptions which were used in the analysis, the scientific uncertainties, and their strengths and weaknesses.

Risk characterization is carried out by scientific and technical experts, but it is not limited to them. Risk assessors and risk managers are again actively involved in the process, as during problem formulation. This is because issues might have arisen which necessitate a reiteration of problem formulation and a repeat of the problem analysis.

Risk Communication

A final responsibility for everyone involved in managing risk is risk communication. This is an ongoing process at the local level and usually involves a government agency, represented by risk managers, industry and other stakeholders, and the public at large.

The objective of risk communication is to maximize the transparency of every activity related to the risk through interaction with the broadest range of interested parties (Figure 2). This objective includes risk identification, analysis, assessment, implementation of the decision, and subsequent monitoring. It is important that the communication process is begun as soon as possible, preferably with an announcement of the project itself.

Risk communication is carried out in a variety of ways. Productive communication is invariably conducted at public hearings when, in theory, everyone listens carefully to each other without any prejudgment of the issue. But this is not always the case, and it is important for the risk managers representing government agencies at such hearings to maintain public trust by their independence and impartiality. Good communication is also achieved by regularly circulating published materials.

Some aspects of risk assessment are scientific and very technical, and therefore it is important that the data and all methods of collection, any models and assumptions that have been applied, and any conclusions drawn are reviewed by peers.

Monitoring for Subsequent Risk

Decisions can be made by the risk manager based on the historical and current information gathered by the team of risk assessors and stakeholders. If the potential risk is assessed as being unlikely, or small, then the risk manager can authorize the project to go ahead. However, it is important that the baseline does not change in such a way that the risk can in fact occur at a

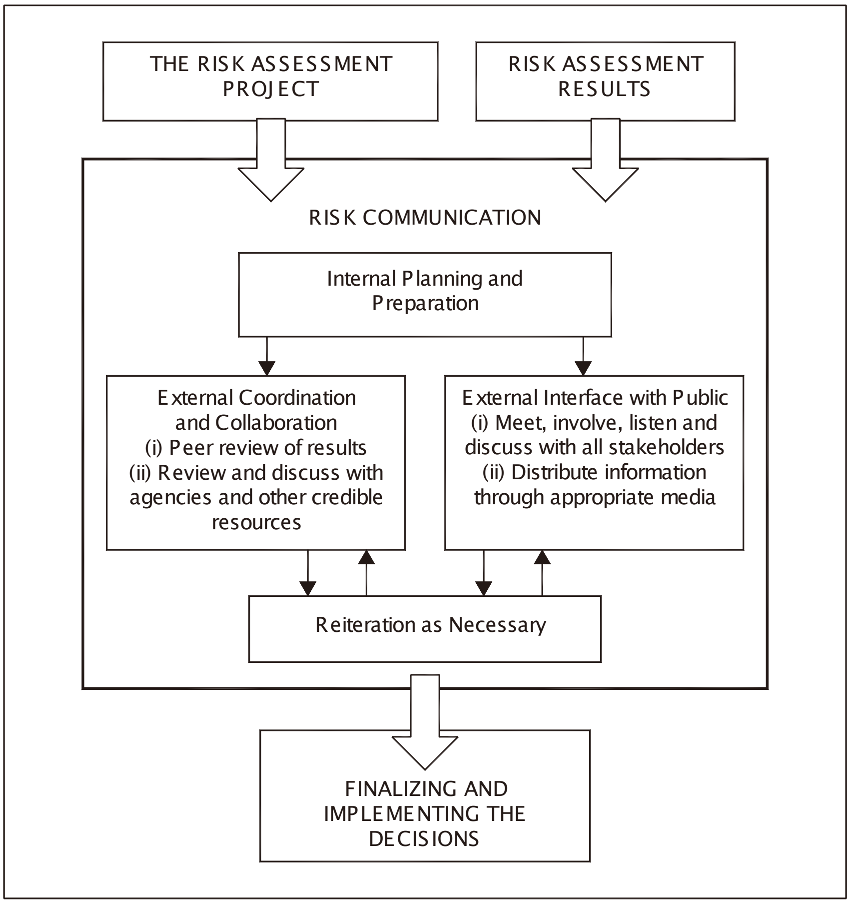

Fig. 2. The process of risk communication for the project and the results.

later time, and therefore the risk manager usually qualifies any decision with the requirement for the continual monitoring of certain site parameters. The task of carrying out the monitoring program may be the responsibility of the regulatory agency, the owners or managers of the project in question, or both.

It is important that any monitoring program is designed around the measurement of:

- standards identified by national legislation and regulation, and
- those parameters relevant to the indication of any increasing risk to the biological end points that have been identified.

Fundamental also to every monitoring program is an exact specification of the methodology. This, for the most part, should have been established during the baseline survey. In other words, reference stations and site stations will be located and fixed along transects on the seabed or at set surface or mid-water distances from identifiable points (such as the perimeter of a facility), and all based on the predominant direction of the current. In addition, the frequency and methods of sampling will be specified, and the methods of analysis will be identified together, where necessary, with laboratory instrumentation.

Global Application of the Framework

Physical Demands of Marine Fish Aquaculture

For the foreseeable future, intensive marine fish aquaculture will be limited to waters of the continental shelf, which is often defined as lying above the 200-m contour. However, for the practical reasons of engineering cost, operational management, and profitability, marine fish aquaculture takes place reasonably close to shore, provided that water quality conditions are suitable.

Selection of a location depends on the proposed fish farming system and practice. Again, because of the investment cost, only intensive fish production is economically feasible, and the options are floating net-pen complexes and buoyant individual cages designed to remain at the surface or to be submerged as required. Net-pen complexes are therefore usually located in coastal estuaries, sounds, and lagoons that have rapid marine water exchange, have some shelter, and provide anchorages that are less than 40 m deep. Individual buoyant cages can be located in less-sheltered waters, and submersible cages can be deployed in deeper water to avoid storms. However, submersible cages have limitations. Although wave energy attenuates with depth, the scale of each unit is limited by potential fatigue of the materials, the capacity of the automated feeders, and the need for regular surveillance and service operations by scuba divers. Scuba divers can operate safely down to a depth of 30 m, but operate most economically around 10-15 m, and working in pairs. Currently, submersible cages are being operated at depths of less than 100 m, but this may still be up to 30 km offshore.

Net-pen complexes are anchored by many separate cables, depending on their formation and size. Additional lines may anchor predator nets. Individual buoyant cages are anchored by four discrete lines which maintain tension all around continuously. Single-point anchor systems have also been used, but at some time the line will become slack, which puts a burden on the cage/line interface. The preferred substrate for the anchors themselves is sand or mud. Anchors can be bolted into rocky substrates, but the practice is costly.

Buoyant cages are designed to operate in currents up to 90 cm/sec, or about 1.74 knots. This is above what is desirable for the fish, which, when confined in strong currents, expend too much energy maintaining their position in the cage instead of growth.

Environmental Demands of Marine Fish Aquaculture

Successful marine fish aquaculture depends on a synergism between the aquaculture site and the farmer. The environmental qualities or parameters of the site must be conducive to the life history and physiology of the species of fish in culture, and the operator must provide an appropriate living space for the fish, meet all their nutritional requirements, and maintain their health.

Site selection for an aquaculture facility is therefore a critical task. It is made difficult because the range of marine ecosystems in which it may be located is diverse, and the suitability of their physical and chemical properties depend significantly on the species and culture practice to be implemented. For example, there are different site demands for submersible cages containing cobia 3-5 km from the coast of Puerto Rico, pens for growing-out tuna in coastal waters within 2 km of the shoreline of Australia, and enclosures for rearing sea bream in shallow marine embayments in the Mediterranean.

The hydrodynamics, nutrient levels, types of pollution, and other environmental parameters found in these locations are all very different. Consequently, there will be differences in the biological end points and their attributes resulting from aquaculture operations that characterize the potential risks to the environment. For example, the risk of eutrophication and change in species diversity in the benthic environment in the poorly flushed lagoons of the Mediterranean is higher than the offshore waters of either Puerto Rico or Australia where there are greater depths and high water exchange rates.

Because of all these differences, each ecological risk assessment has to be tailored to an individual location, and an individual species and aquaculture practice. However, the categories of potential ecological risks and their fundamental methods of assessment are common, and it is only their relative importance that will vary.

A Matrix Approach to Guide the Application of Risk Assessments

In selecting a suitable site for marine fish culture, the ideal requirement is a pollution-free environment in the epipelagic zone with good water quality parameters. Primarily this means year-round high ambient levels of oxygen combined with salinities and temperatures that are between the middle and upper end of the ranges tolerated by the respective farm species, and maintained by a modest current and average tidal rise and fall. Unfortunately the ideal cannot always be found, and the parameters are so diverse that most sites are selected for reasons somewhere between ideal water quality parameters and operational cost and convenience.

As marine fish aquaculture is still in its infancy in most countries, and the locations where it is practiced at the present time are few, for the purpose of these guidelines it is proposed to classify the typical marine aquaculture environment into categories of biogeographical regions or zones and categories of marine epipelagic ecosystem. The definitions of the zones and categories are as follows:

The two biogeographical zones suitable for marine aquaculture (as illustrated in Figure 3) are:

- Temperate waters (10-18℃). Typically cold waters with intrusions of some warmer waters from the subtropics. Temperate waters can be rich in nutrients and highly productive (waters off Australia being an exception), and consequently characterized by low light intensity levels. Temperate waters often support substantial fisheries, together with their dependent populations of birds and marine mammals.
- Tropical waters (>18℃). Typically warm waters with intrusions of some colder waters from the subtropics. Tropical waters are biologically very rich but nutrient poor and characterized by high light levels. Tropical waters often support migratory populations.

The three epipelagic ecosystems are:

1. Offshore waters. Typically 3 km or more from the coast, or up to 100 m in depth, and suitable for submersible cages.
2. Coastal waters. Typically less than 3 km from the coast, or up to 30 m in depth, suitable for submersible cages and floating cages, with strong tidal interchange.
3. Inshore water bodies. Typically semienclosed but large coastal sounds, lagoons, and estuaries, relatively shallow in depth, suitable for floating cages and fixed enclosures, with good tidal flushing.

The 10 categories of risk can then be evaluated in broad terms against each of the 6 generalized marine ecosystems in the form of a matrix (Table 3). The objective is to indicate probable differences in priority relative to each type of ecosystem, and to assist risk managers and risk assessors with their problem formulation. However, the information presented in the matrix does not rule out the uniqueness of some ecosystems, and this most always be considered.

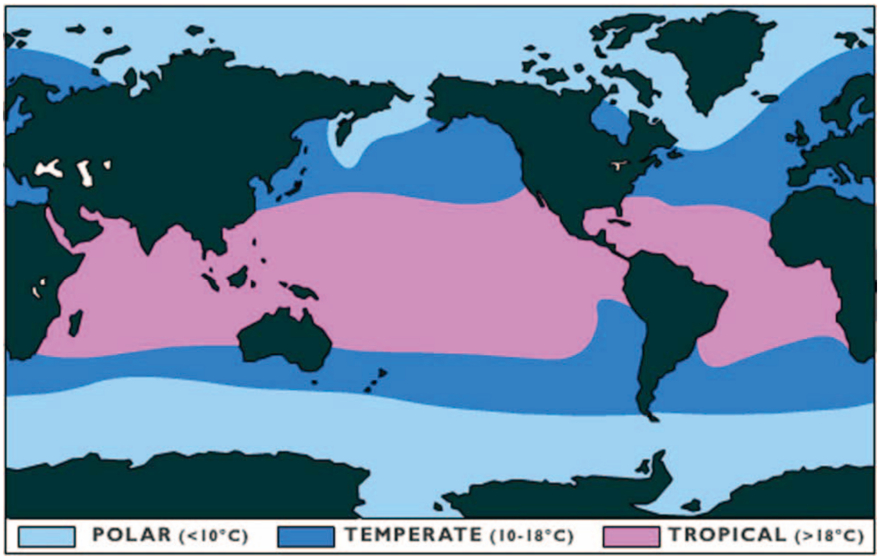

Fig. 3. Broad biogeographical zones for marine aquaculture (courtesy of the Gulf of Maine Research Institute).

Table 3. Matrix to guide the application of risk assessments in the waters of different biogeographic zones.

Category of observed or perceived risk	**Epipelagic ecosystem in temperate waters (10–18°C)**			**Epipelagic ecosystem in tropical waters (>18°C)**		
	Inshore	Coastal	Offshore	Inshore	Coastal	Offshore
1. Increased organic loading	*****	**	*	*****	***	*
2. Increased inorganic loading	*****	**	*	*****	***	*
3. Residual heavy metals	*	*	*	**	*	*
4. Transmission of disease organisms	***	**	**	***	**	**
5. Residual therapeutants	**	*	*	**	*	*
6. Biological interactions of escapes with wild populations	**	**	*	**	**	*
7. Physical interactions with marine wildlife	**	**	*	**	**	*
8. Physical impact on marine habitat	**	*	*	**	*	*
9. Using wild juveniles for grow-out	**	**	*	***	***	**
10. Harvesting industrial fisheries for fish feed	**	**	***	***	***	***

Key: Potential for ecological change without management action
***** Significantly high
**** High
*** Medium
** Low
* Little or none

Risk Assessment Example

Biological Interaction of Escapes with Wild Populations

Risk Hypothesis

Escaped farmed fish, or their gametes liberated from a farm, may pose a risk to wild populations when they interact biologically. Potentially deleterious genetic impacts are perceived to be:

- interbreeding and
- competition for mates or nesting sites.

Potential ecological risks from escaped farm fish are perceived to be:

- competition for habitat and forage,
- increased predation (if piscivores),
- the introduction of exotic pathogens and parasites, and
- amplification of endemic pathogens, some of which may be antibiotic-resistant.

All these possible risks are believed to pose a greater threat to natural populations (conspecifics of the escapees) than to other fish populations at large.

Background Experience

The practices of both freshwater and marine fish culture for stock enhancement or ranching have benefited from years of effort to improve the cultured stocks. In addition to the results of traditional genetic techniques used by hatchery managers, such as trait selection, inbreeding, and out-breeding, there are also the genetic influences of simply surviving in the wild. On the other hand, commercial fish culture is a relatively new field and the present generations of farmed species are still closely allied to the original wild parents. Fish populations bred in captivity have already been subjected to similar stock-improvement practices which, however small, have probably begun to change their genetic makeup. Consequently, when cultured fish are released intentionally or escape from farm enclosures into the ecosystem, they carry with them a genetic profile that can have a deleterious effect should they interact again with natural populations.

There are a number of ways for biological interactions to occur in an aquatic ecosystem where aquaculture activities are practiced. Firstly, farmed fish can escape directly from net-pens and other enclosures due to human error, damage from a catastrophic natural event such as a severe storm, or following damage to the structure by a predatory marine mammal. Secondly, some species of finfish and shellfish that spawn freely in captivity and produce pelagic eggs may release fertilized gametes into the surrounding environment. Thirdly, domestically cultured fish and shellfish raised in hatcheries can be released intentionally on a large scale in annual stock enhancement or sea-ranching programs, leaving them to migrate freely and interact with wild populations.

There is evidence that farmed fish are capable of breeding with their conspecific natural populations in the wild. Therefore escapees may present a genetic threat to a locally adapted natural population through intraspecific hybridization, resulting in a reduction in overall reproductive fitness and recruitment to the wild population. Some interspecific hybridization might also occur should farmed fish escape into an ecosystem where there are very closely related species. The use of reproductively sterile farm fish has been proposed as one means of preventing genetic interactions with wild populations, and consequently reducing their ecological impacts, but this practice is still a matter of priority research.

The introduction of exotic pathogens by the transfer and escape of farmed fish is an issue of lessening concern. This is because most countries have adopted the international protocols regarding the movement of terrestrial and aquatic species for almost any reason, and they have stringent regulations in place regarding the importation of exportation of fish or their eggs specifically to minimize the risk of transferring exotic diseases. Such precautions, however, have not always been effective. Wild fish are the reservoirs of a wide variety of common pathogens, and when certified disease-free fish or shellfish are introduced into an area for the first time they are infected by these dormant pathogens and cause the same diseases endemic to these fish in their native habitat.

Outbreaks of disease can occur at fish hatcheries, and transfer of infected fish may facilitate disease transfer between stocks. However, as the occurrence of endemic pathogens in wild fish is common, it is difficult to determine the extent that pathogen transfer occurs. Similarly, it is difficult to determine the extent to which amplification of endemic diseases occur. It has been suggested that populations of sea lice (such as *Caligis* and *Lepeophtheirus* spp.) are transferred and amplified between farmed salmon and their wild populations, but no scientific evidence has been found (see Appendix D).

Building the Conceptual Model

Escapes may occur with varying frequency and intensity. Therefore, the two sources of biological interactions from the escape of cultured fish or their gametes from aquaculture facilities are catastrophic releases, or periodic natural events such as storms, and chronic releases. Their impact, however, is modified by a number of things, amongst which importantly are the numbers and the genetic characteristics of both the escapees and their resident indigenous wild populations.

Catastrophic releases are unique as they are rare and not planned, and they could involve a large number of escapees. Invariably they can be avoided or controlled if appropriate guidelines are followed for risk management (disaster prevention) and the subsequent recovery of inadvertently released animals. Although it may be impossible to anticipate the occurrence of a 100-year climatic event, a range of possible disasters can be avoided with the selection of a site concomitant with the engineering technology, and away from shipping and navigation lanes and fishing grounds, for example. The effects of a catastrophic release may also be reduced by having a plan and the appropriate equipment for retaining or recapturing escapees.

Chronic releases may be planned or unplanned and may involve large numbers or small numbers of escapees. Planned releases include stock

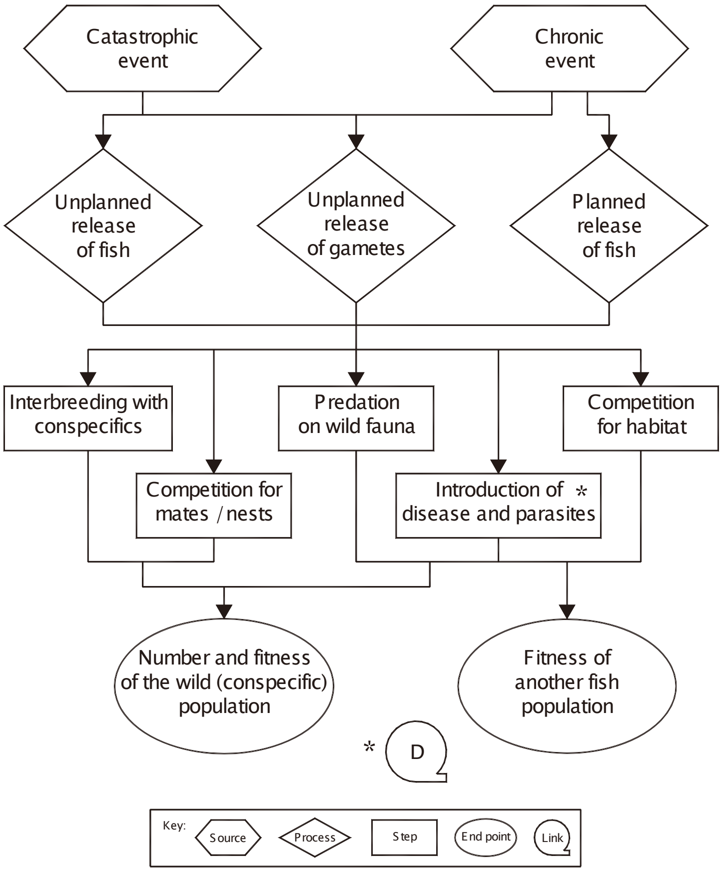

Fig. F-1. A conceptual model for biological interaction of escapes with wild populations.

enhancement and ranching programs by fisheries managers; unplanned releases include the loss of a few fish through a hole in a net made by a predator, or the release of fertilized gametes from a captive stock as a consequence of uncontrolled breeding.

Chronic releases, even due to predator attacks, are therefore often seasonal, but their potential effects for detrimental genetic and ecological interactions may be accumulative. On the other hand, the effects of planned releases of cultured fish are often minimized simply because they are target fisheries for commerce or recreation, and this reduces their potential to interact with the natural population.

Regardless of the manner of escape, escapees may affect the natural population in a number of ways. The most important and direct consequence is interbreeding, followed by the indirect consequence of competition for mates and nesting sites. The effects of interbreeding are a reduction of genetic variance between the two populations, and out-breeding depression. Some other indirect consequences in the short-term may be through competition with all species for forage and habitat space, by predation on endemic fish populations, and the introduction of bacterial or viral pathogens or parasites. The effects of these processes can be a reduction in the genetic integrity of a community or an ecosystem, and they may of course be positive or negative to both. In brief, the outcome can be a reduction in the numerical or genetic strength (fitness) of the wild population, and possibly a reduction in fitness in other fish populations.

Analysis and Characterization

The biological end points and their attributes for protection are:

1) the numerical or genetic strength (fitness) of the wild (conspecific) population, and
2) the fitness of another fish population.

Modern methodologies for measuring the size and genetic parameters of fish populations are all now carried out at the molecular level by analyzing markers, such as mitochondrial DNA and microsatellites. Consequently the techniques are sophisticated and require laboratories well-equipped with costly instrumentation. Protein electrophoresis continues to be a reliable method to detect genetic variation by identifying differences in protein allele frequencies between stocks. More recently, however, protein electrophoresis has been complemented by studies of the genome and the genetic information that can be carried and detected in a small piece of material, such as tissue from liver or muscle, for DNA identification.

Fitness of the Wild Population

Genetically effective population size (or N_e) is the most important factor to sustain a high level of genetic variation within a fish population. This is because in the actual total population (N), only a proportion (the N_e) will pass on their genetic profile to the next generation. If the total population is reduced for some reason, such as the suggested competition with cultured fish, then its original genetic profile may drift further and further away from the original. By measuring this drift, then the genetically effective population size can be calculated and conclusions drawn from the results.

However, calculating the genetically effective population size is not particularly simple. A difficult starting point is having a uniform population, so that selected fish are representative of that population with the same genetic diversity and any local adaptations. For marine fish this is made easier by the fact that few species have been subjected to the same practices of hatchery propagation, restocking, and enhancement as have freshwater fish and anadromous fish, and therefore have little or no introgression.

N_e can be estimated directly by sampling a population at two or more points in time, and separated by a specified number of generations, and it is possible to estimate Ne by the changes in allele frequencies in the interval between sampling. The usefulness of this temporal method has been increased significantly by a technique to extract genetic information from stored samples, which are usually otoliths and scales, where they exist. The polymerase chain reaction (PCR) technique can target a DNA molecule in small and old samples and amplify its genetic information. Unfortunately, fisheries biologists archived material more from freshwater and anadromous fishes than marine fishes, and therefore comparative material might be difficult to obtain.

Fitness is a measure of breeding success or survival. Relative lifetime fitness (%) is therefore the breeding success or survival of one generation to the next. However, the simplicity of this calculation is masked by several possible variables associated with any planned or unplanned releases, such as the number and timing of the release, and the suitability of the receiving ecosystem.

Annual demographic data about the population in question is also important, such as the year-class strength of successive generations. Here, there is potentially more information available for marine species than freshwater species, as demographic data has been required for some time by fisheries managers. It is also important to know when a population has substructures, as these can influence allele frequency changes and misdirect any conclusions.

Fitness in Another Population

The same procedures will be used to determine any reduced fitness in another fish population.

Biological Opinion

Escaped farm fish are not in the economic interest of producers, and there continues to be improvements in the design and operations of marine fish farms to prevent escapes occurring altogether. As many regulators now require notification of escapes, existing records show that the incidence and numbers of escapees continue to decline. However escapes can and do occur, and the escapees may interact biologically with the wild population by changing their genetic integrity or profile, introducing new or unusual genotypes, or by eroding their reproductive fitness, particularly if they are originally from nonlocal stock or selected by the breeders for certain farm traits.

Fortunately the statistical chance of these interactions occurring is affected by a number of factors, the most important of which is opportunity. Escapees are rarely sexually mature, as they are harvested by the commercial growers before nutritional energy is directed to the development of gonads. The few that might be selected as future broodstock at harvest time would be moved elsewhere-usually to a land-based hatchery. Therefore, at the time of escape, escapees are not necessarily mature enough to breed. Secondly, the escapees might not last long enough to mature in the wild and interbreed. There is considerable evidence for a variety of species that the majority of escapees, being raised in captivity on a daily routine of artificial diets, invariably remain in the vicinity of the site to be recovered or fall easy victims of predators. Thirdly, the timing of the escape might not be coincidental with the natural breeding season of the wild population. Catastrophic events may be large but they are also very rare, and chronic events may be continual but usually involve very few fish. Consequently the timing of an escape, the numbers of escapees, and the size of the wild population are all variables which play a role in defining the opportunity for biological interaction.

This is not the same for a planned release of cultured fish from a hatchery, or an unplanned release of fertile gametes from captive adults on a farm. Such events involve the release of a large number of juveniles or gametes that could mature and breed, or a few mature breeders in a restocking program in the hope that they will breed. The opportunities for biological interactions from planned releases of juveniles or broodstock, or unplanned releases of fertile gametes, are obviously considerable, and may be magnified further by the degree to which they have been selected to enhance certain traits.

The potential genetic effects of biological interactions of planned and unplanned releases may also be modified by the population structure of the wild population. For populations with a high degree of local adaptation, among which genetic variability is partitioned at the population level or on a geographical basis, then the natural population structure is particularly at risk from interbreeding with escaped conspecifics. This applies to species of Atlantic (*Salmo* sp.) and Pacific (*Oncorhynchus* sp.) salmon, which are highly structured, and some Mediterranean species, such as sea bass (*Sparus auratus*).

Because of the apparent continuum of the marine environment, it has been thought for some time that most populations of marine fish species are not structured, and therefore their capacity to exert genetic effects is greatly reduced. Species such as the sea bream in the Mediterranean, for example, appear to lack structure at the population level, and gene flow across the range of such species appears extensive. Although farmed sea bream outnumber wild fish, the presence of an undifferentiated stock reduces the potential for adverse interactions. However, the increasing interest in the genetics of marine fish species for fisheries management, and increasing skills in DNA analysis, now suggest subpopulations of some marine species might in fact have remained localized for sufficient time to have developed small genetic differentiation that now are detectable. This adds to the genetic implications for releases and escapees mixing with a subpopulation of conspecifics, although, as noted above, escapees tend to remain close to the culture site, therefore selection of broodstock within the vicinity of the site would be an appropriate practice to reduce this possibility.

There is evidence that fish reared in captivity can lose any natural undiminished capacity to capture prey, and when released or escape they do not compete for forage too well. Escaped fish when recaptured invariably have empty stomachs.

In summary, ecological risks from the biological interactions of unplanned releases with wild populations can be greatly reduced, as they cannot be deleted altogether, by good management practices, such as:

- careful choice of the site;
- constant vigilance of all structures, moorings, and anchorages;
- regularly cleaning nets and predator nets;

- maintaining all navigational requirements (lights and foghorns);
- conducting any transfers with great care; and
- having a plan for escape recovery.

Genetic risks from the biological interactions of unplanned and planned releases with wild conspecific populations can be reduced by:

- selecting broodstock from within the ecosystem of the site;
- selecting marine species for farming, which have little or no substructure; and
- raising sterile animals.

Further Information

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