Guidelines for ecological risk assessment of marine fish aquaculture[1,2]

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ABSTRACT

The purpose of this paper is to exemplify a basic set of guidelines for risk managers and other decision makers to use all information available to assess the different ecological risks of marine fish aquaculture in a variety of marine ecosystems. Ten areas of substantive risk in the interaction between marine fish aquaculture are perceived by the public and public administrators to be of most concern. In this review three of the 10 areas of risk are exemplified for their degree of potential adversity, together with their mitigation, in an identical step-by-step process. These examples outline the approach for conducting a risk assessment for all 10 perceived issues in the paper itself. With the help of a flowchart, the template identifies biological end points or entities and their attributes, both locally and far field, which might be affected for that respective area of risk; and appropriate

[1] This paper is based on a NOAA document edited by the above authors, an outcome of an international workshop held in April 2005 and participated by Kenneth M. Brooks (USA), Stefano Cataudella (Italy), Brett R. Dumbauld (USA), William T. Fairgrieve (USA), John R. M. Forster (USA), Robert N. Iwamoto (USA), David F. Jackson (Ireland), Sadasivam J. Kaushik (France), Michael B. Rust (USA), Philip A.D. Secretan (England), Karl D. Shearer (USA), Ole J. Torrissen (Norway) and Masashi Yokota (Japan).

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methodologies that can be used for measuring or monitoring the effects of exposure to each specific risk. The paper also contains a biological overview of some respective risk, and briefly discusses factors that may enhance or mitigate the risk's occurrence. For the benefit of risk managers and risk assessors in all parts of the world, the risks are framed in a matrix to suggest different orders of relevance for their application in different climatic zones.

INTRODUCTION

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 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 ecosystem components may 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, unless selection has been an informed public choice.

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

BOX 1

Definition of participants in the risk assessment process

Risk manager – Any individual and organization having the responsibility or the authority to take action or require action to mitigate an identified risk. Typically the term describes a decision-maker in a government organization who has legal authority to protect or manage a resource. However, a risk manager may be any interested party who has the ability to take action to reduce or mitigate a risk; for example, the owner or manager of an aquaculture facility.

Risk assessor – A professional who brings a needed expertise to a risk assessment team from any number of relevant fields, including, for example, risk assessment, marine ecosystems, coastal zone management, marine engineering, marine biology, oceanography, aquaculture, fish nutrition, fish disease etc.

Stakeholders – Any individual, company or organization that has a direct or indirect interest in, or could be affected by, an aquaculture operation.

by social choice, such as economic benefits to a local community or issues of public health.

PURPOSE OF THE GUIDELINES DOCUMENT

The purpose of this document is to provide guidelines for risk managers, risk assessors and anyone involved in the risk assessment process (Box 1) to address risks to the environment. All possible fields are listed in Box 1. The specific focus is on the possible effects or impacts of finfish aquaculture, but with several caveats:

- The guidelines are limited only to the assessment of ecological risks. Although, as noted, final decisions are invariably made by risk managers using a broader range of factors, such assessments of economic risks and human health risks by any intervention of aquaculture are not part of this work.
- The guidelines are applicable only to the risk assessment of marine fish aquaculture. The diversity of aquaculture, with its many systems and practices producing more than 200 species of aquatic animals and plants in a variety of fresh and saline waters, is too much to consider in a single document. However, it is anticipated that these guidelines will greatly simplify risk assessments in most other fields of aquaculture.
- The guidelines are confined to the risk assessment of marine fish aquaculture based on its effects on and not from other elements of the environment. Although marine aquaculture is vulnerable to the degradation of water quality as a consequence of poorly managed development in the coastal zone, most countries have regulatory structures and guidelines in place to protect aquaculture, and in time these standards will be improved by combining the risks to the environment from all sources.

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.

BOX 2

Possible contents of a risk assessment report.

- Description of preliminary objectives and plans
- Description of environmental setting for the planned development
- Description of proposed aquaculture practice and species to be cultured
- Review of the conceptual model and assessment end points
- Discussion of major data sources and analytical procedures used
- Review of stressor response and exposure profiles
- Description of risk to assessment end points, including risk estimates and adversity evaluations
- Review and summary of major areas of uncertainty, 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, indication of whether gathering additional data would add significantly to the overall confidence in 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

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 (Box 2), 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 work of risk assessors and risk managers to achieve these objectives. In brief, the guidelines:

- identify the ten 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" subsection on page 10). For those that are important, the respective templates described in Appendices A–J of NOAA Technical Memorandum NMFS-NWFSC-71 (see Appendices list) can be used.

ECOLOGICAL RISK ASSESSMENT OF MARINE FISH AQUACULTURE

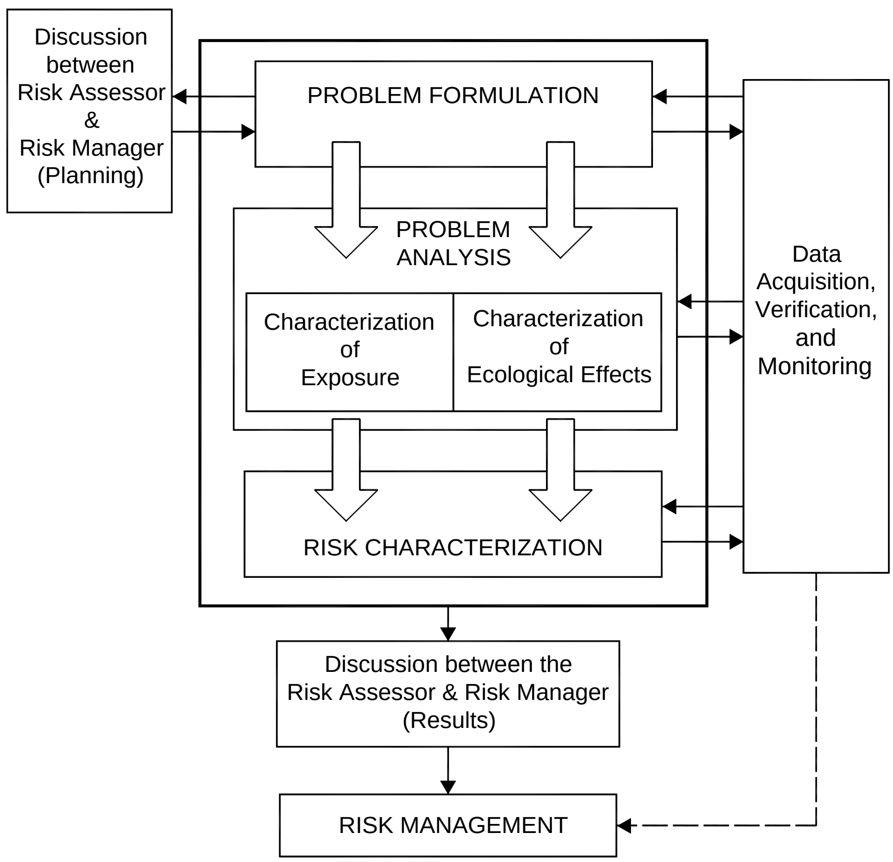
Framework

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 non-chemical 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* (NOAA Technical Memorandum NMFS-NWFSC-71) 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 include 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,

FIGURE 1
The WHO framework for ecological risk assessment



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 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 NOAA Technical Memorandum NMFS-NWFSC-71.

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 culture system being assessed is thought to be organized; and finally,
- the plan for analysing 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 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 ten categories (Table 1). Within these broad designations it is not possible to include all the possible effects that 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 ten 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

TABLE 1
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
	Fish fecal material
	Uneaten fish feed
	Debris from biofouling organisms
	Decomposed fish mortalities on the farm
	Soluble organic loading
	Dissolved components of uneaten feed
	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 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, 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

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/liter).

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 individuals in the natural (conspecific) population;
- the fitness of individuals in 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 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 programme 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 the sediments. These include, for example, metals, and organics such as hydrocarbons, pesticides, polychlorinated biphenyls (PCBs), 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 is 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:

- 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.
- 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.

- An inventory of the species and abundance of the macrobenthic communities. This may be carried out by stratification or by the type of habitat.
- 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.
- A profile of water quality, including temperature, salinity and the potential for stratification as a function of season (pycnoclines and haloclines).
- A profile of primary productivity, including major species (including any toxic species), chlorophyll (Chla), phaeophytin and dissolved oxygen (DO).
- 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.
- 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, 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.

(a) 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, 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 that 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.

(b) 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 programmes 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.

There is some concern about the far-field effects posed by pathogens that may appear on one farm on the stock held in another. Indeed, the probability of pathogens from one farm site spreading to another within x tidal cycles provides much of the basis for licensing and management in some countries.

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 semi-quantitative factors or by 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 that were used in the analysis, the scientific uncertainties, and their strengths and weaknesses.

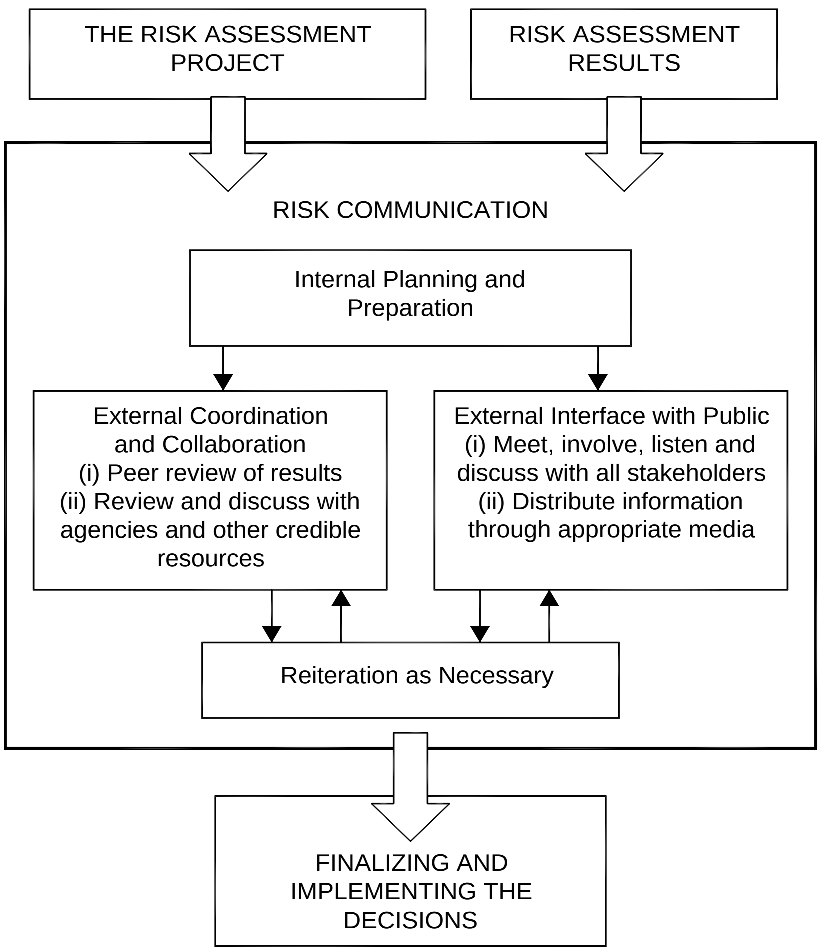
Risk characterization is carried out by scientific and technical experts, but it is not limited to them. Risk assessors and risk managers are again actively involved in the process, as during problem formulation. This is because issues might have arisen that necessitate a reiteration of problem formulation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

FIGURE 2
The process of risk communication for the project and the results



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 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 programme 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 programme 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 programme 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 that 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 seabream 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 in 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

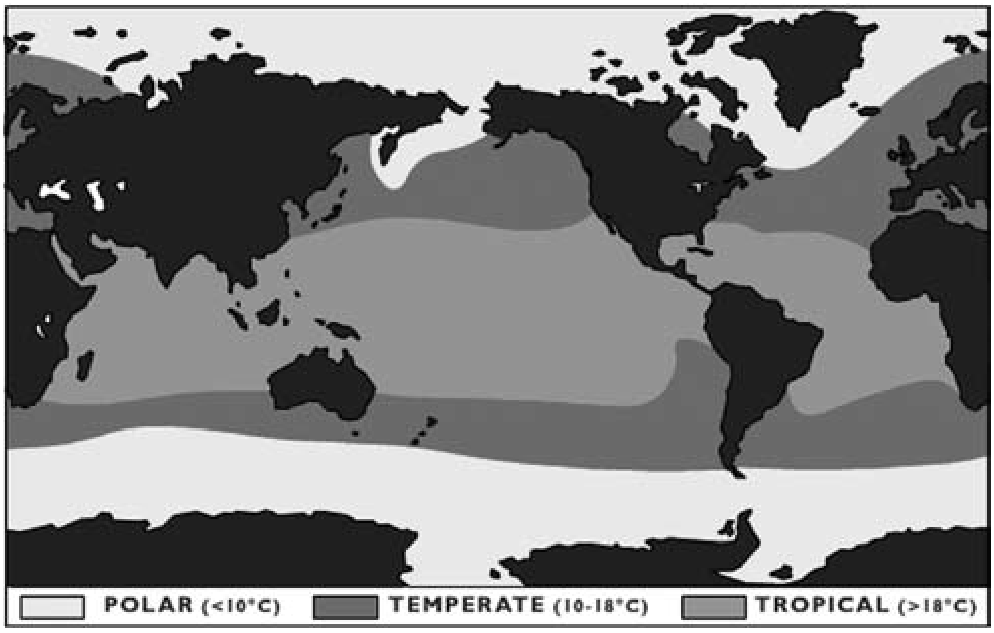
In selecting a suitable site for marine fish culture, the ideal requirement is a pollution-free environment in the epipelagic zone with good water quality parameters. Primarily, this means year-round high ambient levels of oxygen combined with salinities and temperatures that are between the middle and 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 °C). 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 °C). 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:
  - Offshore waters. Typically 3 km or more from the coast, or up to 100 m in depth, and suitable for submersible cages.
  - 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.
  - Inshore water bodies. Typically semi-enclosed but large coastal sounds, lagoons and estuaries, relatively shallow in depth, suitable for floating cages and fixed enclosures, with good tidal flushing.

The ten categories of risk can then be evaluated in broad terms against each of the six generalized marine ecosystems in the form of a matrix (Table 2). 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 must always be considered.

FIGURE 3
Broad biogeographical zones for marine aquaculture



Courtesy of the Gulf of Maine Research Institute

TABLE 2
Matrix to guide the application of risk assessments in the waters of different biogeographic zones[1]

	Epipelagic ecosystem in temperate waters (10–18 °C)			Epipelagic ecosystem in tropical waters (>18 °C)		
Category of possible risk	Inshore	Coastal	Offshore	Inshore	Coastal	Offshore
1. Increased organic loading	*****	**	*	*****	***	*
2. Increased inorganic loading	*****	**	*	*****	***	*
3. Residual 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	**	**	***	***	***	***

[1] Key: Potential for ecological change without management action: *****Significantly high, ****High, ***Medium, **Low , *Little or none.

GLOSSARY OF RISK ASSESSMENT AND MARINE TERMS

(a) Risk assessment terms[3]

Adverse ecological effects. Changes that are considered undesirable because they alter valued structural or functional characteristics of ecosystems or their components. An evaluation of adversity may consider the type, intensity and scale of the effect as well as the potential for recovery.

Assessment end-point. An explicit expression of the environmental value that is to be protected, operationally defined by an ecological entity and its attributes. For example, marine turtles are valued ecological entities, and the survival of individual migrating turtles is an important attribute.

Attribute. A quality or characteristic of an ecological entity. An attribute is one component of an assessment end point.

Characterization of ecological effects. A portion of the analysis phase of ecological risk assessment that evaluates the ability of stressor(s) to cause adverse effects under a particular set of circumstances.

Characterization of exposure. A portion of the analysis phase of ecological risk assessment that evaluates the interaction of the stressor with one or more ecological entities. Exposure can be expressed as co-occurrence or contact, depending on the stressor and ecological component involved.

Community. An assemblage of populations of different species within a specified location in space and time.

Conceptual model. In problem formulation, a visual representation and written description of predicted relationships between ecological entities and the stressors to which they may be exposed.

Ecological entity. A general term that may refer to a species, a group of species, an ecosystem function or characteristic, or a specific habitat. An ecological entity is one component of an assessment end point.

Ecological risk assessment. The process that evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors.

Ecosystem. The biotic community and abiotic environment within a specified location in space and time.

[3] Source of risk assessment terms: US EPA, 1992, *Guidelines for ecological risk assessment.*

Exposure. The contact or co-occurrence of a stressor with a receptor.
LC50. A statistically or graphically estimated concentration that is expected to be lethal to 50 percent of a group of organisms under specified conditions.
Measure of effect. A change in an attribute of an assessment end point or its surrogate in response to a stressor to which it is exposed.
Measure of exposure. A measure of stressor existence and movement in the environment and its contact or co-existence with the assessment end point.
Population. An aggregate of individuals of a species within a specified location in space and time.
Receptor. The ecological entity exposed to the stressor.
Recovery. The rate and extent of return of a population or community to some aspect(s) of its previous condition.
Risk characterization. A phase of ecological risk assessment that integrates the exposure and stressor-response profiles to evaluate the likelihood of adverse ecological effects associated with exposure to a stressor.
Source. An entity or action that releases to the environment or imposes on the environment a chemical, physical or biological stressor or stressors.
Stressor. Any physical, chemical, or biological entity that can induce an adverse response.

(b) Marine terms

Benthos. Collectively all those animals and plants living on or in sediments at the bottom of the sea. Benthic animals are usually described by their position in the sediment relative to the surface and their size, i.e.:

- **Infauna**. Fauna living within (burrowing in) the sediments, and
- **Epifauna**. Fauna living at or on the sediment surface. They can be sessile or slow moving, and may spend some time in the water column.

Bioremediation. Biological recovery.
Demersal. Living on or near the bottom of the sea.
Epipelagic. Pertaining to the community of suspended organisms inhabiting an aquatic environment between the surface and a depth of 200 m.
Halocline. Well-defined vertical salinity gradient in the water column.
Nekton. Collectively the macroscopic animals suspended in the sea, moving about independently of currents (includes fishes and whales).
Pelagic. Of or pertaining to the open waters of the sea (beyond 20 m depth).
Porewater. The water retained in the pores between the grains of the sediment.
Pycnocline. Well-defined vertical density gradient in the water column.
Seston. Collectively all living and dead suspended microscopic animals and particulate matter in the sea.

APPENDIXES

Appendices A through J of NOAA Technical Memorandum NMFS-NWFSC-71 are templates that outline the approach for conducting a risk assessment for each of the ten areas of marine fish aquaculture perceived by the public and public administrators to be of most concern. The titles of the appendices are listed below:

- Appendix A: Increased Organic Loading
- Appendix B: Increased Inorganic Loading
- Appendix C: Residual Heavy Metals
- Appendix D: Transmission of Disease Organisms
- Appendix E: Residual Therapeutants
- Appendix F: Biological Interaction of Escapes with Wild Populations
- Appendix G: Physical Interaction with Marine Wildlife
- Appendix H: Physical Impact on Marine Habitat
- Appendix I: Using Wild Juveniles for Grow-out
- Appendix J: Harvesting Industrial Fisheries for Aqua-feeds
- Appendix K: Workshop Participants
- Appendix L: Sources of Further Information