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Guidelines for Ecological Risk Assessment of Marine Fish Aquaculture

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Guidelines for Ecological Risk Assessment of Marine Fish Aquaculture

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Executive Summary

Risk assessment is frequently defined as a tool for making decisions under conditions of uncertainty. Therefore it is far from being an exact science and yet it thrives on exact information. At this period in the emergence of the field of marine fish aquaculture, the scientific and technical knowledge of aquaculture's effects on the environment are a growing compendium of information, but at times the information appears to be ambiguous, conflicting, and incomplete. This is because it is being gleaned continuously from a diverse range of marine ecosystems where there are different fish and shellfish species being produced under a variety of systems and practices which, in some cases, are themselves still being developed.

But the time when knowledge is apparently deficient is arguably the right time for seriously addressing risks, and the constraint of incomplete scientific and technical knowledge has to be offset by the practical knowledge and professional experience of individuals in order to make balanced judgments. In the near future it will be possible to model the interactive ecological effects of marine aquaculture activities, and decisions will be made based on risks quantified numerically for different ecosystems. However, for the moment, informed decisions will have to be made by risk managers with the help of responsible individuals guided mostly by their past experiences and research.

The purpose of this document is to provide 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 no order of priority they are: increased organic loading, increased inorganic loading, residual heavy metals, transmission of disease organisms, residual therapeutants, biological interaction of escapes with wild populations, physical interaction with marine wildlife, physical impact on marine habitat, using wild juveniles for grow-out, and harvesting industrial fisheries for aqua-feeds.

In this technical memorandum each of these 10 areas of risk is assessed for its degree of potential adversity, together with its mitigation, in an identical step-by-step process. This common analytical framework, which is first described and illustrated in detail, was developed by the World Health Organization many years ago, and its generic nature and international acceptance make its use for the risk assessment of marine fish aquaculture an ideal application.

Appendices A through J are templates that outline the approach for conducting a risk assessment for all 10 perceived issues. With the help of a flowchart, each template identifies the biological end points or entities and their attributes, both locally and far field, which might be affected for that respective area of risk. It also identifies appropriate methodologies that can be used for measuring or monitoring the effects of exposure to each specific risk.

The chances of any risk occurring can differ greatly in accordance with the natural characteristics of the local ecosystem and its geographic location. Therefore, each template contains a biological overview of its respective risk and briefly discusses factors that may enhance or mitigate the risk's occurrence. In addition, for the benefit of risk managers and risk assessors in all parts of the world, the 10 risks are framed in a matrix to suggest different orders of relevance for their application in different climatic zones. Each template contains a list of documents where further pertinent information can be found.

Finally, this technical memorandum contains a glossary of the risk assessment terms and marine terms used throughout, a list of the international participants of the workshop, and a list of references specific to marine aquaculture and risk assessment, but broader in nature.

Acknowledgments

These guidelines for risk assessment were compiled by scientific delegates from Australia, France, England, Ireland, Italy, Japan, Norway, Scotland, and the United States of America. The International Workshop was funded by NOAA Fisheries Service, the European Union Directorate for Fisheries and Maritime Affairs, and the respective institutions of the delegates.

The workshop participants especially acknowledge the help of Glenn Suter II, of the U.S. Environmental Protection Agency, who facilitated the workshop, Susan Thomas of the Battelle Marine Science Center and Shannon Stragier of the Pacific Marine Fisheries Commission, who acted as stenographers, Langley Gace of Ocean Spar Technologies, who provided insight into the realities of offshore aquaculture engineering, and the Pacific Aquaculture Caucus, which handled the logistics of the meeting. None, however, is responsible for the contents of these guidelines.

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 lifestyle 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 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.

Purpose of the Guidelines Document

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

1. 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.
2. 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 aquaculture fields.
3. 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.

Table 1. Definition of participants in the risk assessment process.

Participant	Definition
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.

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 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 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" subsection on page 11). For those that are important, the respective templates (as described in Appendices A–J) can be used.

Table 2. 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

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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 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.

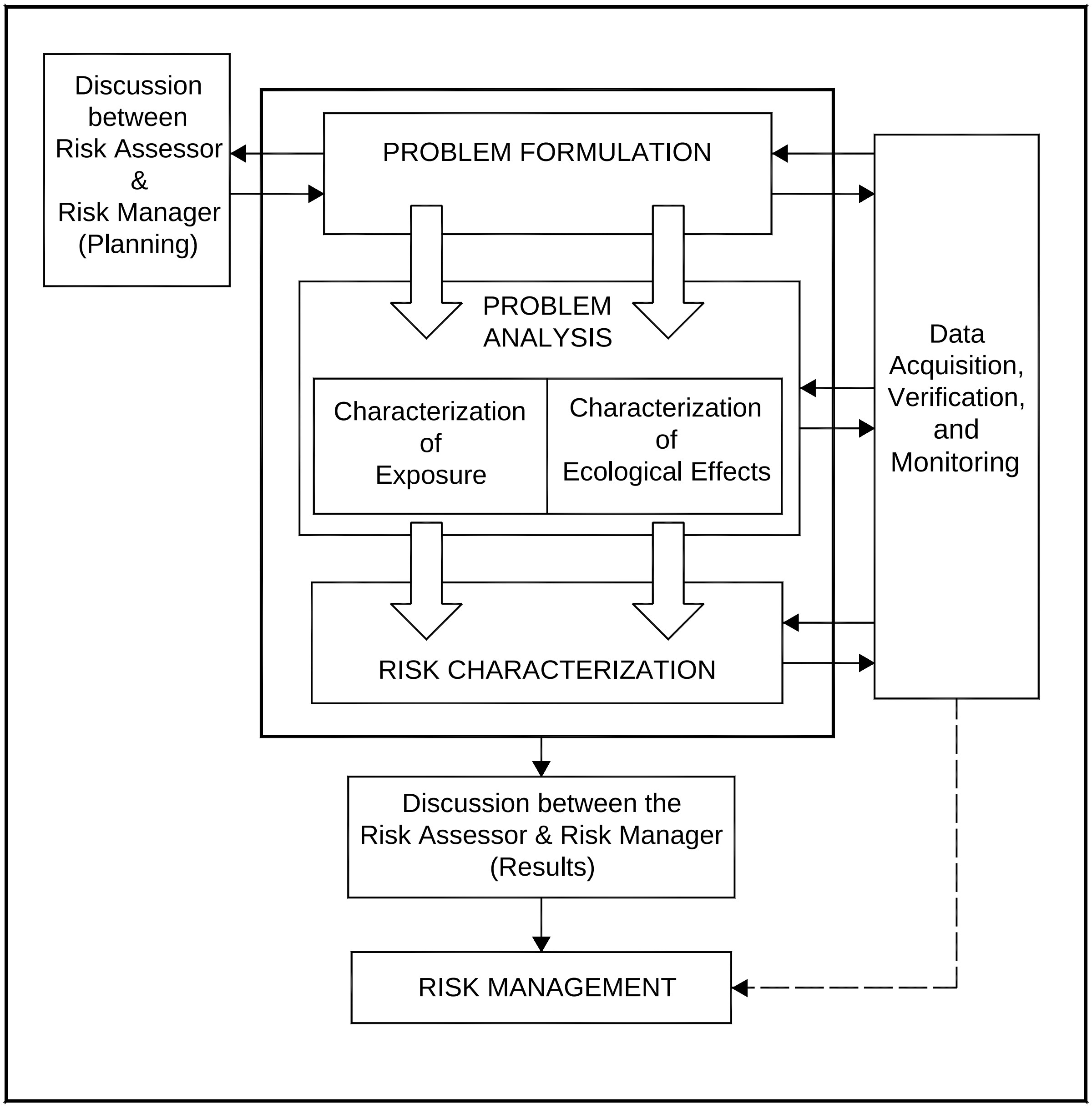

Figure 1. The WHO framework for ecological risk assessment.

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 3). 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).

Table 3. 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

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 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, 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

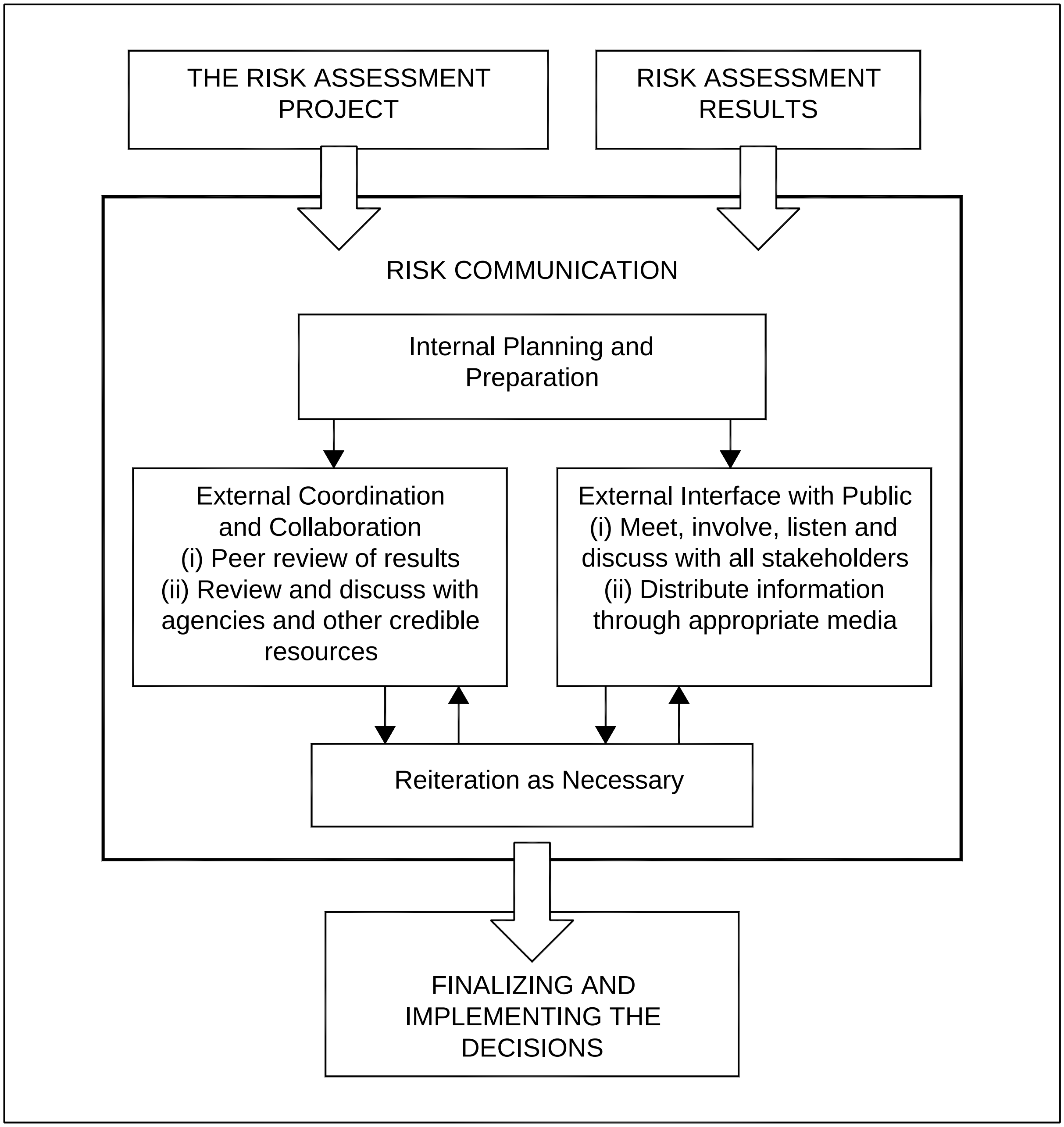

Figure 2. The process of risk communication for the project and the results.

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 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˚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.

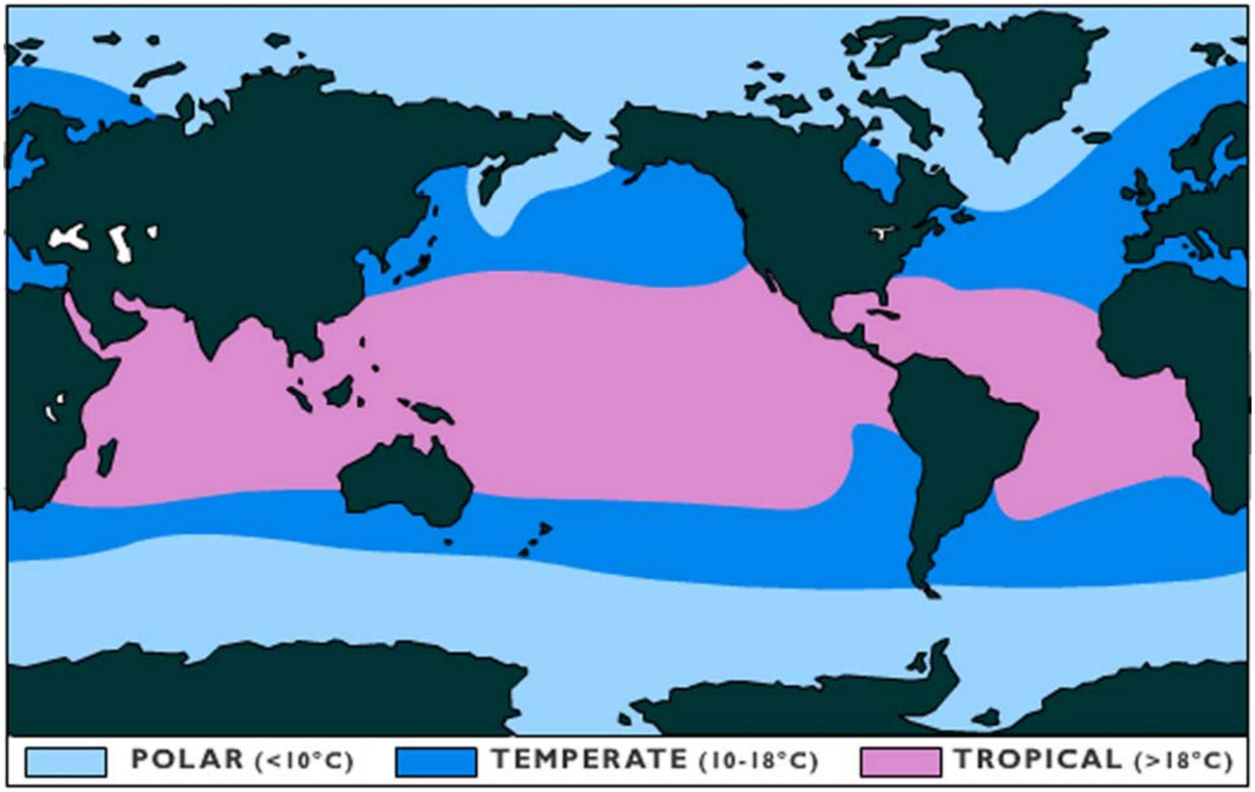

Figure 3. Broad biogeographical zones for marine aquaculture (courtesy of the Gulf of Maine Research Institute).

- 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:

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 4). 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.

Table 4. 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

Glossary

Risk Assessment Terms

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.

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% 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.

(Source of risk assessment terms: U.S. EPA, 1992, Guidelines for Ecological Risk Assessment)

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.:

1. **Infauna.** Fauna living within (burrowing in) the sediments,
2. **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.

Appendices

[Editor's note: Appendices A through J are templates that outline the approach for conducting a risk assessment for each of the 10 areas of marine fish aquaculture perceived by the public and public administrators to be of most concern. Figures A-1 through J-1 are flowcharts for the conceptual models. The templates are not presented here in any order of priority.]

Appendix A: Increased Organic Loading

Risk Hypothesis

Particulate organic waste produced by the high concentration of biomass at any marine fish farm is deposited directly on the substrate beneath the farm, or is distributed downstream in suspension or solution. The organic matter is mostly made up of particulate fecal matter and uneaten feed, but may also include the accumulation of marine fouling organisms falling or purposely removed from the units, together with decomposed mortalities and possibly some harvest wastes. The perceived risk is that the accumulation of organic matter may reach a point where the alterations in sediment chemistry become noxious to a particularly valuable macrobenthic fauna or to exclude an unacceptable portion of the benthic community.

Background Experience

Physico-chemical and Biological Effects of Organic Enrichment

Organic wastes from aquaculture are formed mainly from feces and uneaten feed and are primarily made up of carbon compounds. These wastes break down quickly, increasing the biological oxygen demand (BOD), which can in turn reduce the oxygen content of the sediment. Naturally occurring bacteria then strip oxygen from sulfate, leaving sulfide, a common form of sulfur found in low concentrations in marine environments. Some carbon and sulfide enrichment of benthic sediments should be expected in nearly all forms of intensive aquatic animal production, but the response by the benthic invertebrates differs widely. When enrichment becomes too great, sensitive species may be excluded and opportunistic species proliferate, thus changing benthic communities.

Organic enrichment associated with labile aquaculture waste creates BOD in sediments that can exceed the assimilative capacity of the local environment, especially in a less-dispersive environment. In these instances, the added organic material, that is, biodeposits measured as total volatile solids (TVS), or organic matter content is an additional source of food for macrobenthos, leading to increased community abundance, and increased macrobenthic biomass. Increasing BOD creates physicochemical changes in sediments characterized by increased TVS and free sulfides, and decreased redox potential. These physico-chemical changes can force biological changes on specific taxa, which can alter macrobenthic communities. Benthic faunas sensitive to enrichment, such as brittlestars (Ophiuroidea), may be extinguished from the area below a net-pen farm, and replaced by organic-tolerant opportunistic annelids and capitellids.

Spatial Extent of Effects

There is equivocal evidence that the effects of volatile organic material may extend beyond the perimeter of a farm complex, especially when fish stocking densities are high. These effects, which can be measured during point-in-time surveys, are generally referred to as near-field effects, and their extent and degree of benthic impact are determined primarily by the degree of flushing in and around a facility, and to a lesser extent with the biomass of the animals being cultured.

Appropriate siting of intensive aquaculture facilities is critical to the management of any potential benthic effects. Computer models, such as DEPOMOD, are available to assist in predicting the extent and degree of organic deposition at proposed facilities. The spatial extent of measurable effects has only been documented from the area under intensive systems to about 205 m down current from their perimeter. Significant adverse effects, when they occur, have generally been restricted to distances less than 60 m from the perimeter of intensive cultures.

As the number of aquaculture facilities in a coastal ecosystem increases, the potential for far-field effects increases. These effects are the result of all of the cumulative organic discharges from both upland and water-dependent activities. While near-field effects generally occur and remediate quickly, far-field effects are more subtle and require long-term monitoring programs or computer modeling for detection. However, because far-field effects can be widespread and may be long-lasting, a precautionary approach to their management is warranted, increasing the need for careful risk analysis as aquaculture industries expand and mature—particularly in small or restricted bodies of coastal water.

Temporal Aspects of Benthic Effects

In terms of risk, prolonged case studies reveal that the physico-chemical and biological changes in the benthic sediments associated with aquaculture sites are reversible. Chemical recovery, as characterized by a return to preproduction concentrations of TVS, reduced free sulfide concentrations, and increased redox potential to positive values, normally occurs within periods of less than a year for return to pristine conditions at well-flushed sites, but longer at those which are poorly flushed. Biological recovery occurs concurrently with chemical recovery, but frequently takes an additional invertebrate recruiting season to develop fully.

In summary, the effects of organic enrichment in sediments of well-chosen sites appear to be local and reversible, provided that appropriate management practices, such as stocking density and fallowing regimes, are followed. However, as the number of facilities and the overall biomass of cultured organisms increase, there is need for risk analyses assessing far-field, cumulative effects associated with all forms of organic discharge to coastal ecosystems.

Building the Conceptual Model

The sources of organic wastes from marine fish aquaculture operations are the fecal material of the farm fish, any uneaten fish feed passing through the enclosure, dead cultured fish that might be left to decompose, and biofouling debris that might fall naturally from the accumulation on the structures or during cleaning. This waste is dispersed by currents.

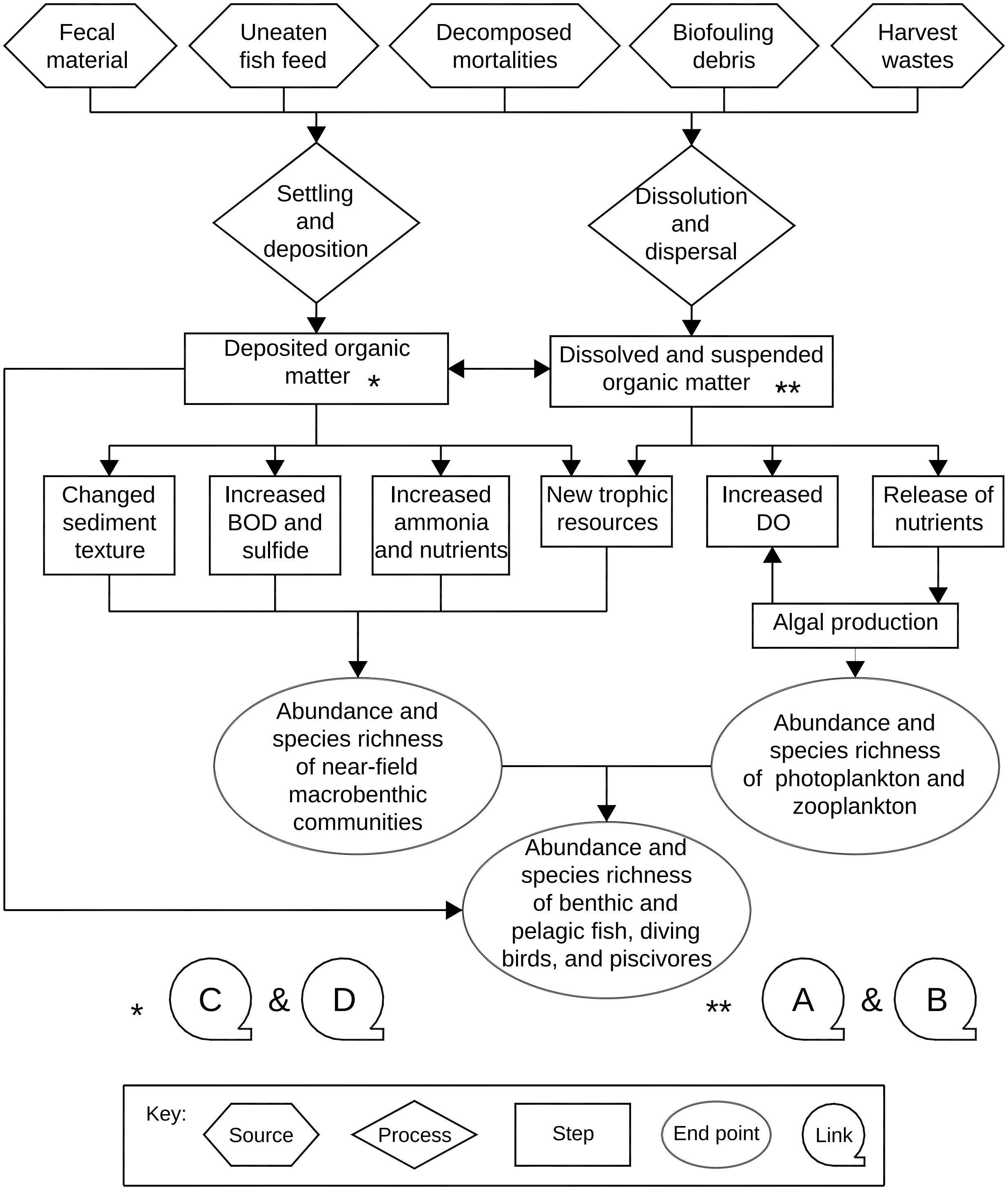

Figure A-1. A conceptual model for increased organic loading.

During its fall to the sea bed, or immediately following disturbance of the sea bed, a small part of the solid organic waste will become suspended as particulate matter or be dissolved in solution. The majority of the solid waste, however, will fall directly and accumulate in the underlying sediments.

The organic matter deposited on the sea bed has a number of effects. It may change the texture of the sediment physically by covering and infiltrating the original sediment. It may also change the chemistry of the sediment by introducing metals, such as copper and zinc (see Appendix C), which may be toxic, and by increasing the BOD, ultimately inducing anaerobic conditions. These effects in turn lead to changes in the microbial communities with nitrates reduced to ammonia and sulfates to hydrogen sulfide. Finally, an excess of biodeposits can cause dramatic changes to the sediments biologically by attracting different species and eliminating others.

The first end point with its attributes of all these effects is the species richness and abundance of the benthic microinvertebrates, including both infauna and epifauna. As these fauna are at the base of aquatic food webs, subsequent end points and their attributes are the species richness of benthic fish and pelagic fish, together with diving birds and other piscivores. These populations can also be affected directly by the added food resource provided by feces and uneaten feed.

For the most part, the small volume of solid organic waste that becomes suspended particulate matter or is dissolved has effects which are described in more detail in Appendix B. The first effects include the release of nutrients into the water column, particularly nitrogen and phosphorus; oxygen levels may be affected, and the changes may attract different trophic resources. Secondly, the availability of more nutrients increases the production of phytoplankton, but these effects are much less than those caused by the direct release of ammonia and other nutrients into the water column from fish metabolism. However, sediments act as a reservoir of potential nutrients and can be a source of efflux long after the fish pens have been removed.

Analysis and Characterization

Although marine fish farms are preferably sited where a current maintains a high rate of water exchange, the evidence is that nearly all particulate organic waste is deposited within a few tens of meters from the perimeter of the containment structure. Therefore the effects are localized and accumulative.

The biological end points and their attributes for protection are:

1) the abundance and species richness of the near-field macrobenthic communities,
2) the abundance and species richness of phytoplankton and zooplankton, and
3) the abundance and species richness of benthic and pelagic fish, diving birds, and piscivores.

Macrobenthic Communities

Near-field effects associated with particulate organic waste have been studied in detail for over 20 years, and the effects are well understood. Consequently there is a rich body of literature describing the physicochemical and biological response to varying degrees of sediment enrichment.

The affected community is the macrobenthos—including infauna and epifauna. Exceeding the assimilative capacity of the benthos leads to physico-chemical changes in the sediment that include increased BOD and decreased redox potential. Biological changes include a shift to anaerobic microbial communities (e.g., *Desulfovibrio* spp. and ultimately *Beggiatoa* spp. mats), resulting in increased concentrations of free sulfide and ammonia, which are toxic to individual taxa at varying concentrations. It has been shown that an increase in free sulfides ($S^=$, HS, and H_2S) from background concentrations of less than 100–300 µM to 1,000 µM results in the exclusion of half the reference number of taxa in annelid-dominated communities. In mollusk-dominated communities, increases from background to 450 µM have resulted in a similar decrease in species richness of 50%. The extent of these changes depends on fish production levels, water currents, sediment grain size, water depth, and other factors.

Computer models, such as DEPOMOD, are readily available to predict the deposition of organic matter around aquaculture facilities, given that appropriate information is available describing bathymetry and hydrodynamics of the site and the necessary inputs regarding the physiology of the cultured fish species. Measurable effects, based on the evidence from coastal salmon aquaculture, typically extend to distances of 150–200 m from the perimeter of the culture containment system, at water depths of 30–100 m, average current speeds of 3–10 cm/sec, and maximum current speeds of 25–75 cm/sec.

Performance standards prescribed by regulatory authorities are usually defined to establish the limits of the allowable effects. The output from a model such as DEPOMOD can then be used to assess the probability that the characteristics of a proposed aquaculture facility (such as species, size at harvest, total production, type of feed, feed conversion ratio, etc.) will be able to comply with the stated performance standards.

Phytoplankton and Zooplankton

The effects of increased organic loading on phytoplankton and zooplankton populations in the water column are generally much less than those attributable to direct nutrient release into the water column, and should be considered as part of increased inorganic loading (see Appendix B). While some specific effects can be noted, such as an increase in benthic copepods and isopods that feed directly on the deposited organic matter, these are usually of limited concern for the whole ecosystem. Some phytoplankton species migrate vertically through the water column and these may be able to access benthic nutrients not readily available to species higher in the water column, thus conferring an ecological advantage.

Benthic and Pelagic Fish

Studies with baited traps indicate that scavenger fish (usually benthic species) can be attracted to the food accumulating under net-pens. This can lead to increased populations of specific species and altered food-web dynamics. It would be unusual for these effects to lead to system-wide changes, although clearly the number of fish pens and amounts of uneaten feed are key factors here.

Biological Opinion

Organic wastes deposited on the marine substrate can have definite effects on sediment chemistry and macrobenthic invertebrates, and therefore sediment organic enrichment is the primary local effect of concern for most marine fish aquaculture sites. The principal constituents of wastes from fish farm enclosures are feces and uneaten feed. About 12% by weight of ingested feed is ejected as feces, as modern diets are about 87–88% digestible, and 3–5% of feed can be lost to the environment. As feed costs are the highest operating cost, feeding statistics are rigorously followed and monitored in detail by calculating conversion rates, observing with underwater telemetry, and using new technologies of feed delivery to minimize wastage.

Other possible constituents of organic wastes and biodeposits are minor by comparison. Few fish carcasses remain to disintegrate and pass down to the sediment. Mortalities, which are typically less than 10% annually, are usually removed manually every day and disposed of appropriately. Similarly, modern best management practices require all nets to be removed and cleaned of fouling organisms onshore, and therefore there is no longer a significant residue being placed on the benthos, and harvesting wastes and waters are typically retained on the harvest vessel or at an onshore facility.

There are local effects associated with high-density aggregations of marine fish. But risks can be minimized through proper site selection, which can be enhanced by adequate preproduction risk assessments ensuring that effects on particularly valuable resources are avoided and that environmental risks to the cultured species are acceptable. Near-field hazards can be effectively managed using performance standards that producers are required to meet. Inexpensive physicochemical surrogates have been frequently substituted for more expensive and time consuming biological evaluations and standards. The costs of near-field risk assessments and monitoring are normally defrayed by the producer.

In summary, benthic effects created by intensive aquaculture are local and reversible. The effects can be minimized by careful site selection and site operation, and observing best management practices, with particular attention to:

- proper siting in areas where the waste does not accumulate deeply,
- avoiding sensitive and valuable habitats,
- maintaining appropriate stocking densities,
- removing carcasses daily,
- collecting all harvest wastes,

- cleaning nets of biofouling organisms regularly on vessels or on land, and transferring debris to approved landfills,
- monitoring feed regimens to reduce any loss, and
- rotation of farm sites (fallowing) to enable bioremediation.

Benthic effects are monitored and managed through the establishment of performance standards defining allowable effects. Chemical changes are best assessed inexpensively by monitoring the TVS, Eh, and free sulfides. Biological changes can be monitored by benthic faunal assessment using either manual sorting and identification, or much cheaper video techniques. Compliance monitoring is often required as part of a permitting process or waste management programs. Ongoing studies and monitoring results have demonstrated that these management programs are effective tools for managing environmental costs associated with this form of producing food.

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Appendix B: Increased Inorganic Loading

Risk Hypothesis

Marine fish farms present a high concentration of biomass compared with natural settings. High concentrations of nutrients are contributed to the water column from fish metabolism, and to a lesser extent from fish feed, feces, and biofouling organisms. Mostly these are untreated dissolved nitrogen and phosphorus in inorganic and organic forms. The perceived risk is that these soluble compounds may cause eutrophication of the coastal zone with concomitant reductions in dissolved oxygen levels as the additional organic matter is degraded, or production of nuisance blooms of toxic algae and reductions in light penetration resulting in the loss of submerged aquatic vegetation.

Background Experience

In most marine environments, nitrogen is the limiting nutrient. However, upwelling brings enormous amounts of nitrogen and other nutrients to the surface along the western shores of many continents. The result is that these areas are generally not nutrient limited. In the high latitudes of temperate waters, on the other hand, primary production is generally light limited, although there may be protected bays in some areas where eutrophication may be a hazard.

Fish excrete ammonia and ammonium waste primarily across gill epithelia but also in concentrated urea, which in oxygenated waters is converted into nitrite and nitrate nitrogen. Nitrogen and phosphorus are also dissolved by the water column from uneaten feed and feces during and after descent through the water column.

Ammonia and hydrogen sulfide can be released from underlying sediments covered with feces and uneaten feed as sulfate and nitrate-reducing bacteria degrade organic carbon. However, studies reveal that there is usually little soluble hydrogen sulfide gas in the water column. About 98% of the sediment gases are methane and carbon dioxide.

Dissolved oxygen levels decrease with fish respiration and the oxidation of sediment waste. Monitoring over long periods in coastal waters of the northeast Pacific Ocean reveals a maximum oxygen reduction of 2 mg/L in water passing through net-pens where large biomasses of fish were being fed, and in most cases the reduction was less than 0.5 mg/L. Theoretically, oxygen may be depressed in water overlying enriched sediments, but this effect has not been well documented.

Harmful algae vary in their response to nutrient loading, depending on the species, habitat, timing, and loading rate. Harmful algae known to kill marine fish and shellfish, or pass on risks to human health, typically originate elsewhere and not near a farm site. Some species smother the gills of aquatic organisms, while others are digested and concentrated to levels which may be toxic when consumed. The source of cells or cysts may just as well be from a shallow bay inshore, or from coastal waters well offshore, so an understanding of the phytoplankton dynamics of the entire region is important.

The causes of nuisance algal blooms are difficult to establish. The dynamics of phytoplankton nutrient uptake in temperate waters result in cell-division times of 1–2 days during which phytoplankton will be transported many kilometers from the location where the nutrients were released. Conditions that promote phytoplankton blooms include high nutrient loadings, water column stability associated with freshwater inputs (stratification), low winds, and periods of neap tides. In higher latitude temperate climates such conditions are most frequently found in sheltered bays receiving large freshwater inputs.

Building the Conceptual Model

The sources of dissolved nutrients from marine fish aquaculture operations are the physiological and respiratory functions of the farm fish themselves, and in trace elements and micronutrients (vitamins) in any uneaten feed. Additional nutrients may be contributed from breakdown of organic matter in the sediments (see Appendix A, and below).

Nutrients can pass into solution in several ways. Most nitrogenous waste is passed across the gills of fish. Excreted ammonia and urea, together with other nitrogenous and phosphorus compounds, are excreted directly into the water column. Additional small inputs may be contributed as feces and uneaten feed pellets fall to the seabed, but the majority fall and accumulate in the sediment.

Sediment bacteria are responsible for the continuous and sometimes elaborate cycling of nitrogen between ammonia, nitrite, nitrate, and dinitrogen gas, and convert sediment phosphorus into soluble inorganic phosphorus. The majority of these inorganic nutrients, together with particulate organic nitrogen and soluble organic nitrogen, are all available for assimilation by phytoplankton and other primary producers, such as macroalgae.

Most of the inorganic nitrogen and phosphorus in the sediment is ultimately remineralized following particulate adsorption or advection, and thus can be taken out of the cycle temporarily. These nutrients add to cumulative effects in the far field. Their release rates are not well characterized, but their contribution is small in relation to the dissolved nutrients released directly into the water column during fish respiration.

Analysis and Characterization

Marine fish farms are typically located at sites where a current maintains a high rate of water exchange. Therefore nutrients going into solution as a result of farming activities are quickly diluted and directed by the current away from the site. Consequently, with the possible exception of some immediate effects on local sessile flora and fauna, the effects will be more distant and cumulative, possibly culminating with impacts on marine fish and shellfish following eutrophication or oxygen supersaturation.

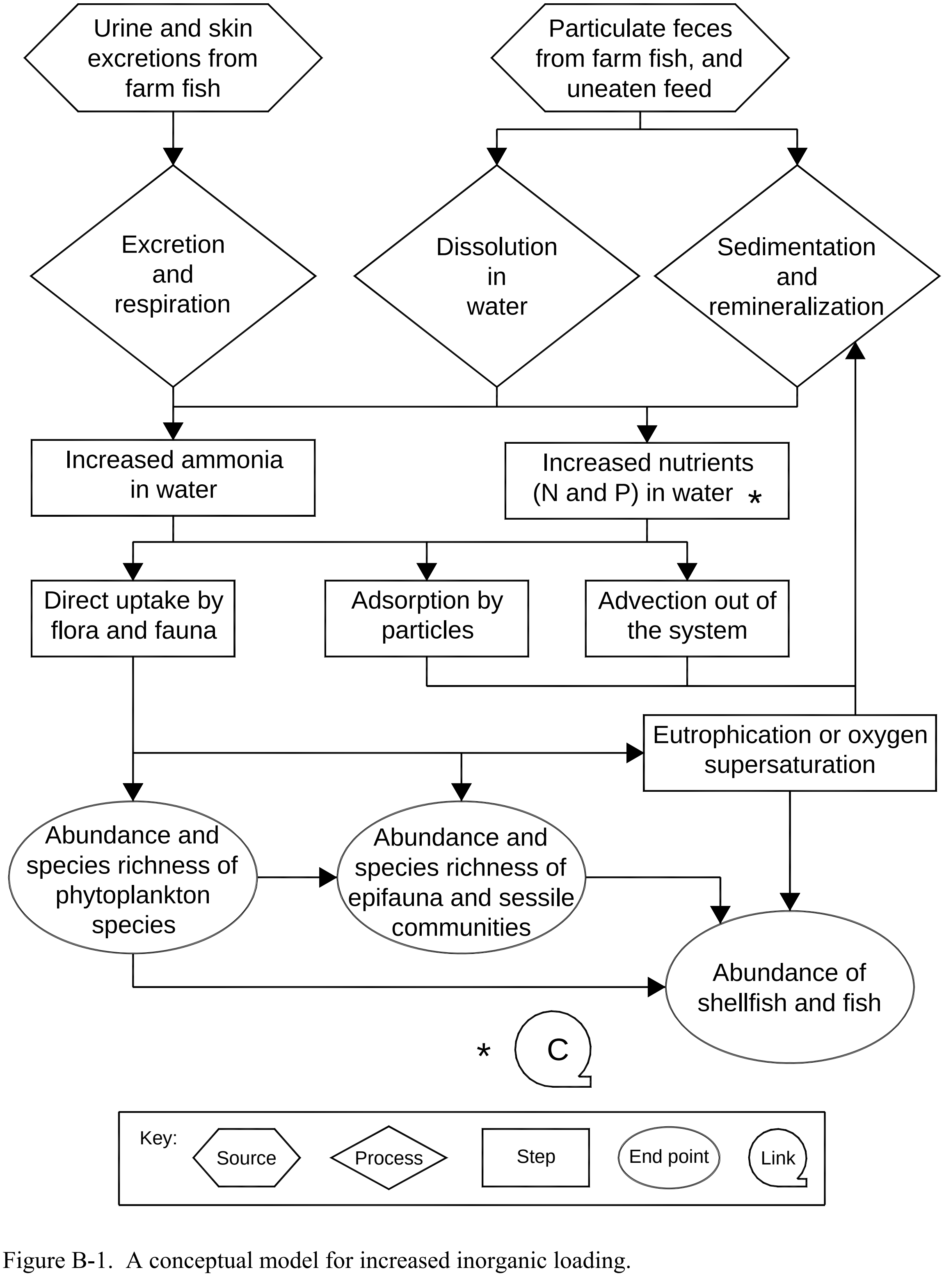

Figure B-1. A conceptual model for increased inorganic loading.

The biological end points and their attributes for protection are:

1) the abundance and species richness of phytoplankton species and associated grazers in the receiving waters,
2) the abundance and species richness of local epifauna and sessile communities (macroalgae, epiphytes, biofouling organisms, and filter feeders), and
3) the abundance of shellfish and fish.

Phytoplankton Species and Associated Grazers

Concentrations of dissolved phosphorus and inorganic nitrogen tend to be greatest in proximity to their sources. However, because of the temporal and spatial dynamics of nutrient uptake by suspended particulate matter in flowing water, there is little potential for measuring enhanced phytoplankton production around aquaculture facilities in open aquatic ecosystems—regardless of the amount of dissolved inorganic nutrients added to the water.

Local Epifauna and Sessile Communities

Some degree of observable effect is likely in the local epifauna and sessile communities subjected to continuous exposure. This is often demonstrated qualitatively by the increased biomass of biofouling organisms, together with changes in the species composition of attached nitrophylic green algae (*Ulva* spp. and *Enteromorpha* spp.), and sessile or localized filter feeders.

Localized effects are also more noticeable in shallow waters, where the substrate is still in the euphotic zone. Here, dissolved nutrients from aquaculture sources can increase, decrease, or extirpate communities of benthic microalgae (microphytobenthos, mainly diatoms), subsequently impacting macrobenthic grazers.

The dilution of metabolic wastes is a function of currents. Therefore a box model approach can be used to determine their potential effects. This is supported by inputs determined by mass balance with the known-effects concentrations for the species under culture, or known nutrient releases from the species as a function of size and feeding regime. Predicted concentrations will be highest on the down-current perimeter of the containment system during periods of minimal current speeds, and these can be compared against water quality criteria or published-effects concentrations. Typically, these are based on the most sensitive species, which predominantly will be the species in culture as they are usually at greatest risk.

In far-field receiving waters, effects associated with numerous point and nonpoint sources are generally experienced by all living resources in that particular hydrologic unit, but the sources cannot be identified or distinguished specifically. In confined receiving waters near to concentrated aquaculture activities, the cumulative effects from multiple sources could lead to changes detectable by long-term monitoring programs. On the other hand, far-field effects from aquaculture activities in very open bodies of water become increasingly unlikely.

The potential for far-field effects is best assessed through computer models and long-term monitoring by a coordinated consortium of contributors to the cumulative effects.

Shellfish and Fish

Because conditions of eutrophication or oxygen supersaturation generally occur on some ecosystem scale, such as in a bay or a fjord, all aquatic plants and animals resident in the system may be affected by the induced changes. In an oligotrophic system, for example, the added nutrients may result in increased productivity. However, in a nutrient sensitive environment where the assimilative capacity is already challenged, then any eutrophication can cause widespread loss of productivity at a number of trophic levels, including fish and shellfish resources and their predators.

Biological Opinion

Water flow rates through buoyant fish cages and net-pens is massive, therefore the flow and large volume means that measurable effects in the water column are hard to detect at more than a modest distance downstream. Monitoring dissolved nitrogen around net-pen farms in Europe, Canada, and the United States has revealed only small increases in levels around the perimeter of farms, and were undetectable about 30 m downstream, and monitoring dissolved oxygen has been discontinued in some areas, other than by the producers for their own use during hot weather.

The majority of coastal waters are naturally replete with nitrogen and phosphorus, but there are times (usually in spring or summer) when nutrient supply, usually but not always nitrogen, can limit the growth of marine phytoplankton populations; other factors include light availability, sinking below the compensation depth, or grazing by predators. Marine waters vary in their sensitivity to nitrogen addition. For example, well-mixed, fast-flushing habitats that are light limited are much less sensitive than vertically stratified, poorly flushed habitats, often inshore and depleted of nitrogen at the surface. Such highly sensitive areas are often characterized by prolific blooms of toxic or noxious algal species, and they are avoided by farmers siting fish enclosures as they are well known to be unsuitable.

Marine waters over the coastal shelf vary between being well-mixed and highly stratified, and any one condition may last from days to months. Periods of nutrient sensitivity do occur but invariably they are shorter in northern latitudes. Marine waters in southerly latitudes are more susceptible to algal bloom stimulation if an adequately large external source of nutrient is applied. However, the extent of any problem depends on a number of external factors, such as the nutrient ratio balance, far-field circulation patterns, the occurrence of harmful algae or cyst beds, and perhaps the proximity to coral reef habitats. On the other hand, phytoplankton are a primary base of marine food webs, so increased production in open offshore zones is sometimes beneficial. As there are currently few marine fish farms sited in semitropical coastal waters, they cannot be counted as a source of nutrients.

Dissolved nutrients may result in increased local production of attached macroalgae, but eutrophication associated with aquaculture is not a local effect. It is an ecosystem effect that can change restricted coastal areas, such as bays or estuaries. This is because it takes 1–2 days for phytoplankton to take on nutrients and divide, and 6–7 cell divisions (6–14 days) for a background phytoplankton density of 20,000 cell/L to reach a nuisance bloom density of greater than 1 million cells/L. By this time, even with small net current vector speeds of 1–2 cm/sec, nutrients released from an aquaculture facility might have traveled 10–24 km from their point of introduction.

Consequently, depending on the scale of operations, it is unlikely that a single aquaculture operation will release sufficient nutrients to affect phytoplankton production adversely in open coastal waters. However, as the number of fish farms increases, more attention should be paid to nutrient balances and the potential for increasing effects on an ecosystem basis. These system-wide effects can be cumulative, and their assessment and management requires an understanding of all of the nutrient sources to a water body, including upland and water dependent contributors. Local monitoring using point in time surveys is not recommended. Monitoring and management on a system-wide basis are required to maintain the health of coastal ecosystems. Nutrient inventories, together with mass-balance models, and system-wide, long-term monitoring programs initiated early in the development of an area for aquaculture, are the recommended strategies for management.

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Appendix C: Residual Heavy Metals

Risk Hypothesis

Compounds of the heavy metals copper and zinc are a necessary part of marine fish farming in some form. The perceived risk to the marine environment is that they may accumulate in the sediments to toxic concentrations in a biologically available form.

Background Experience

Copper and zinc are essential micro-minerals for the nutrition of fish, and they are obtained from the natural diet or absorbed through the gills and skin. In fish husbandry they are administered as trace elements in the diet. Therefore it is highly probable that there will always be a mineral supplement in fish feeds that is compounded in an appropriate chemical form.

Trace elements in the feed after digestion are evacuated in fecal material, and they are also available in uneaten feed. Consequently, they are present in the particulate organic waste deposited on sediments near the farm. There are several pathways by which these trace elements enter the water column.

Copper, copper sulfate, or copper oxide, are the primary ingredients of many government-approved marine antifouling paints used to reduce the fouling of aquaculture structures, such as net-pens. Benefits of reduced fouling include increased water flow through the pens; decreased drag, which can compromise the moorage or structural integrity of the system; and decreased oxygen loading to the benthos around the farm.

Building the Conceptual Model

From the background experience, copper and zinc are the two heavy metals used in some form in marine aquaculture. At low to moderate concentrations, dissolved ions of these metals become toxic in the water column in sediment porewater. The primary sources of zinc from marine fish farms are the fish fecal matter and uneaten feed. Uneaten feed and fecal matter are minor sources of copper. The major source is leaching and flaking of antifouling paints that might have been used to protect equipment or applied to nets.

There are a number of processes and intermediate steps between these sources and the biological or ecological end points that are of concern. Both particulate fecal matter and uneaten feed containing zinc settle onto the sediment. Under aerobic conditions, zinc is dissolved in the water column and contributes to the background level of the ecosystem. Even slow currents dilute these inputs, and toxicity associated with dissolved copper or zinc associated with marine aquaculture is not expected. Under anaerobic conditions, zinc is bound by sulfides in the

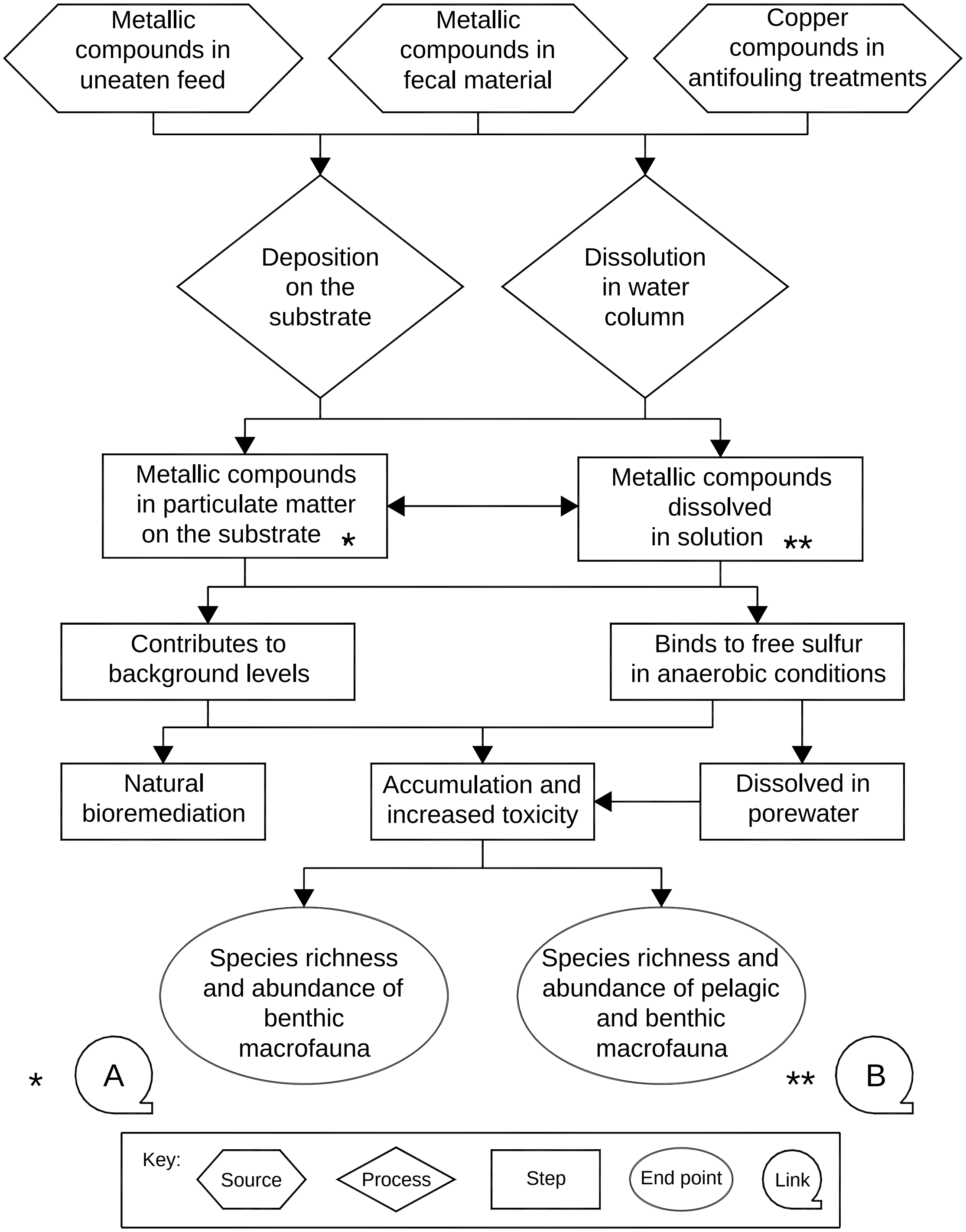

Figure C-1. A conceptual model for residual heavy metals.

sediment, significantly reducing its biological availability. During chemical remediation, the sulfide is oxidized to sulfate and the zinc enters that water as a dilute free ion.

Copper, similarly, from its three sources, may be dissolved in the water column contributing to the background level. In the sediment it is also bound, subsequently undergoing chemical remediation.

In areas of very poor flushing, or in the absence of appropriate best management practices, there is the remote chance that levels of copper and zinc may reach toxic concentrations. As this might have an effect on the marine ecosystem, some guidelines would be required for its protection.

Analysis and Characterization

The biological end points and their attributes for protection are:

1) the species richness and abundance of the seston and nekton, and
2) the species richness and abundance of the infauna and epifauna.

Seston and Nekton

Proximal fauna in the seston, nekton, and epifauna can be exposed to increased background levels of ionic copper and zinc in the water column. The exposure and its effect are continuous. Levels of copper and zinc in the water column are determined by standard sampling procedures and laboratory analysis using a graphite furnace atomic absorption spectrophotometer with a GTA 100 graphite system.

Many national or their provincial jurisdictions have established chronic and acute freshwater and marine water quality standards for heavy metals, including copper and zinc. The levels are usually quoted in micrograms per liter (µg/L) or parts per million (ppm).

Infauna and Epifauna

Proximal fauna in the infauna and epifauna can be exposed to increased background levels of ionic copper and zinc in the sediments following remediation. Again, both the exposure and the effect are continuous. Metals are bioconcentrated by many organisms, leading to increased concentrations in comparison with those found in the water. Levels of copper and zinc in the water column are determined by standard sampling procedures and laboratory analysis.

Numerous sediment quality benchmarks are available in various jurisdictions. However, regulatory programs for sediments have proven more difficult to develop, and few jurisdictions have published such criteria. Available benchmarks include the apparent effects threshold, threshold effects level, and probable effects level. Levels are usually quoted in micrograms of the metal per gram (µg/g) of dry sediment.

Biological Opinion

After digestion, residual metallic compounds are evacuated in feces. But their volume is extremely small, as heavy metal ingredients of manufactured feeds are absolutely minimal and they are digested efficiently. They are also available in waste feed that passes through an enclosure uneaten. However, modern feeding practices are designed to minimize waste feed and therefore that volume is also very small. This is because feed manufacturers now use proteinated forms of zinc, such as the zinc methionine analog, which are more digestible than zinc sulfate. This has greatly reduced the required concentrations in feed and therefore any subsequent environmental loading of this metal.

Contamination of marine sediments by copper-based marine antifouling treatments has been greatly reduced by best management practices for net-cleaning and retreatment. These practices now call for these operations to be carried out on protected, land-based sites, with biofouling debris deposited in an approved landfill.

Residual copper and zinc in sediments beneath net-pens and cages, from whatever source, are both reduced to nontoxic levels as they combine with sulfides in organically enriched sediments. High concentrations of sulfides can reduce their bioavailability quickly, and the process is particularly rapid in anaerobic conditions. Concentrations of zinc have been shown to return to background levels during chemical remediation as both sulfides are oxidized to sulfates, and there has been no buildup under the fish enclosures.

Sequestering of copper by fish is predominantly in the liver and kidneys, and not in muscular tissue, and sequestering of zinc is greatest in the eye, followed by the kidney, bone, skin, gill, and liver, with only minute traces in the muscle or gonads. Therefore these two metals, which are not particularly toxic to mammals, pose little or no human health risks.

In summary, no adverse effects to the marine environment from the presence of copper and zinc from fish farm enclosures should be anticipated providing there is:

- appropriate selection of copper or zinc compounds as mineral supplements in manufactured feeds,
- a properly managed feeding regimen in operation to minimize wastage, and
- proper use of government-approved antifoulants, with upland net cleaning and disposal of all biofoulants in an approved landfill.

This biological opinion is probably applicable to both biogeographical zones and the epipelagic waters of all three ecosystems where fish rearing in marine enclosures might occur.

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Appendix D: Transmission of Disease Organisms

Risk Hypothesis

Both cultured and wild fish are susceptible to the same pathogens and the same parasites in the aquatic environment, as all are part of the naturally occurring flora and fauna. The risk hypothesis is that intensive aquaculture conditions manifests the prevalence of indigenous or exotic disease agents in an area. The exposure of wild fish to disease is therefore increased directly with the water moving freely between farm enclosures and the local ecosystem, or indirectly when farmed fish escape and intermingle with wild fish (see Appendix F).

Background Experience

For disease to occur, pathogens and parasites require a susceptible host and an aquatic environment conducive to themselves but stressful to the host. Fish undergoing stress have increased susceptibility to invasion. Their immune system is overcome, and their health is then impaired. The rate of disease transfer is dependent on the virulence of each agent and the susceptibility of the host, which can, of course, be manipulated by preventative measures such as vaccines.

Intensive systems themselves are not necessarily the cause of stress among farm fish, as shoaling is invariably part of their natural behavior, but stress can occur when there are abnormal changes in ambient environmental conditions or natural meteorological phenomena: for example, continuing algal blooms caused by prolonged high water temperatures, or “winter chill” when temperatures may be unseasonably low. Stress can also be induced by certain conditions on the farm, mostly associated with poor management practices. These may include, for example, overcrowding, failure to collect mortalities daily, bleeding fish on-site at harvest, and introducing juveniles or broodstock not certified as being disease-free.

Disease can also occur if exotic pathogens and parasites are unwittingly introduced into an ecosystem from another geographic region. The origin of these exotic agents may be, for example, the ballast water discharged from ships or any unregulated movement of live aquatic animals for commercial purposes. The majority of nations enforce strict import regulations to prevent the introduction of alien pathogens via all live animals, including marine fish. But transfers can occur; for example, the white spot syndrome (Baculovirus complex) in penaeid shrimp was introduced into South America from Asia as a result of illegal movements and improper health inspections prior to shipment.

Building the Conceptual Model

The sources of the risk of increased disease transmission are the natural background pathogens and parasites in the respective marine ecosystem, and any exotic pathogens or parasites that might be introduced unknowingly.

The systems and intermediate steps in the model are few and direct. Infected wild fish first transfer their disease agents to farm fish, or infected exotic fish transfer their exotic agents to both receptive farm fish and wild fish. The result is cross-infection and cross-infestation between farmed fish and wild fish, increasing possibly to chronic or perhaps catastrophic conditions in that local ecosystem. Effects could also be extended to other, more distant ecosystems if infected or infested farm fish escape and subsequently transfer their disease agents to wild fish in another ecosystem.

At the end of these steps there are possible conditions in the marine ecosystem that put a number of biological entities at risk. These are the end points, and they are qualified by certain attributes. The health of wild fish may be debilitated as they might carry above-normal loads of pathogens and parasites, and some wild populations may be reduced in number following any epidemic. If this should occur, then the survivors would benefit by an increased natural immunity to that particular agent.

Analysis and Characterization

The biological end points and their attributes for protection are:

1) the health of wild fish,
2) the numerical strength and diversity of wild fish populations, and
3) the natural immune resistance to disease of some fish.

Health of Wild Fish

Wild fish in the proximity of fish farms may be involved in the transfer of disease agents, and may have background levels of disease organisms (pathogens and parasites) higher than normal. It is necessary to determine the natural background levels of the local disease flora and fauna, and estimate the effects of increased loads of individual pathogens and parasites on wild fish by an individual series of laboratory dose response (exposure) studies for each agent, and developing a simple probability model. In time it may be possible to model multiple disease agents, similar to those used in agriculture and human health.

Strength and Diversity of Wild Fish

In the case of a disease epidemic, catastrophic mortalities of both wild and farmed fish might occur. In order to measure such an effect, it is necessary to have some prior estimate of the natural diversity of the local fish populations and their strengths in the area. For commercial species, this information may be available from fisheries managers.

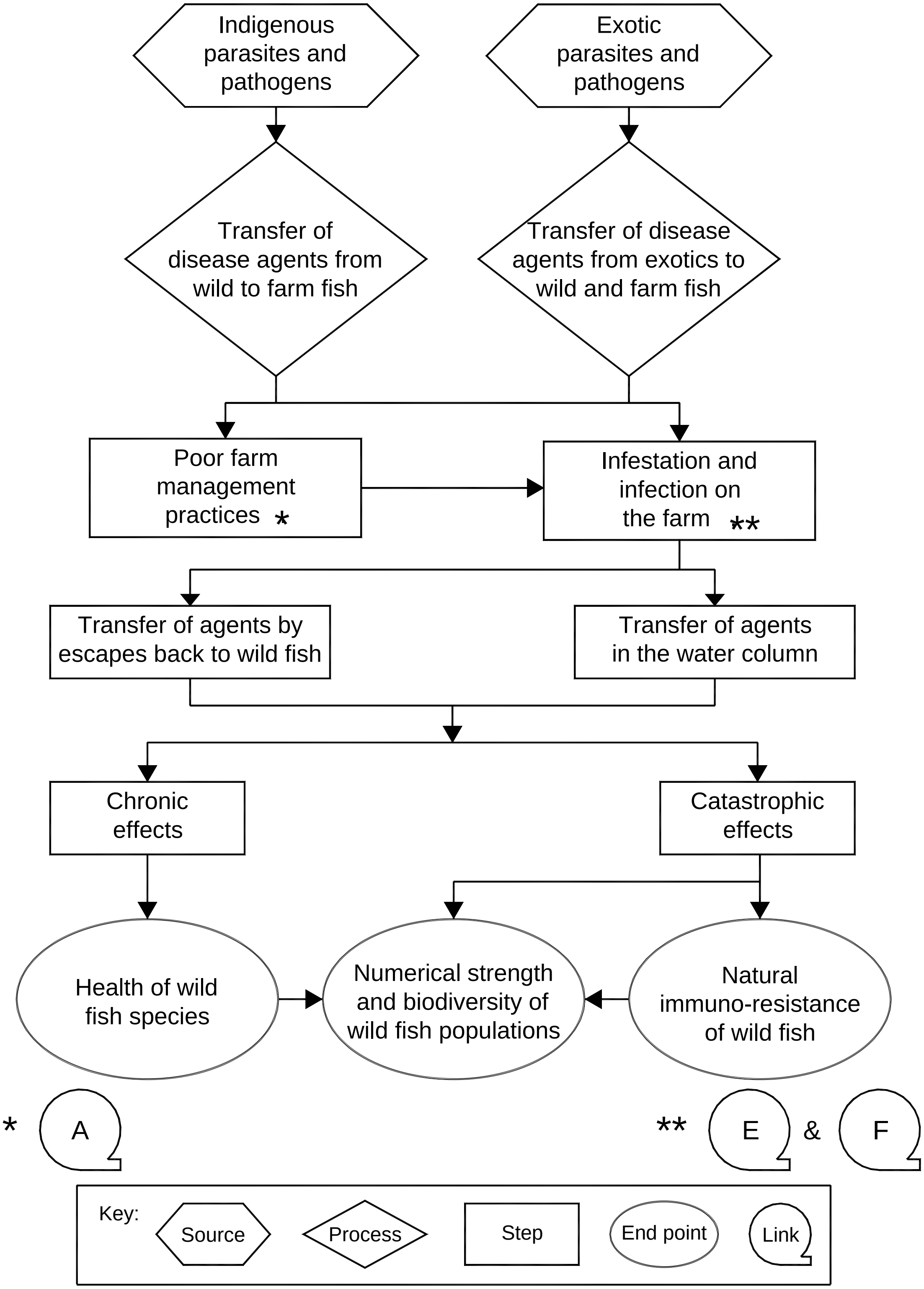

Figure D-1. A conceptual model for the transmission of disease organisms.

Natural Immunity of Wild Fish

The natural immunity of some wild fish populations to disease organisms can be improved if a large number of individuals susceptible to a certain disease agent are eliminated by an epidemic. Should an incident ever occur, measuring its effects on the survivors would have to be derived through combination of the analyses and characterizations of the two biological end points and their attributes, as described above.

Biological Opinion

Because of the close proximity of fish in an enclosure, it is possible for pathogens to spread through the population and multiply sufficiently to overcome the fish immune systems, causing an outbreak of disease. The trigger is stress, which may be caused by a sudden change in ambient environmental conditions, or perhaps handling during farm operations. The same phenomenon occurs in populations of wild fish. Significant disease events have been observed when large numbers of wild fish aggregate, such as at spawning time, or when there are stressful environmental conditions, such as prolonged elevated water temperatures in summer. However, scientific studies have shown that, within a few meters of a net-pen fish complex experiencing an outbreak of disease, the level of pathogens is insufficient to cause disease in nearby healthy wild or farmed fish.

Experience also indicates most farmed fish that escape remain close to their enclosures waiting to be fed. Hence they become easy victims of predators. Those that escape and survive are probably not infected to begin with, but for infected fish that do survive their chances of being responsible for an outbreak in wild fish is remote. This is because they are not introducing a new pathogen to wild fish, a few escapees are unlikely to generate enough pathogens to result in an epidemic among in wild fish, and environmental factors play the larger role in triggering a disease event than the mere presence of a pathogen.

There are very many species of marine fish parasites, each with specific life histories. Very few are seriously harmful to fish or man, and their presence is only inadmissible if it affects the commercial product. One such group of parasites is the Caligidae, or copepods, commonly called sea lice, and in particular *Caligis* spp. and *Lepeophtheirus* spp. These are ectoparasites and the adults are readily visible on the skin of fish, causing disfiguration.

Some sea lice are host-specific, while others have numerous common hosts. Sea lice larvae are released into the water from eggs incubated by adult lice resident on fish hosts. The larvae drift on tides and currents as they develop until they reach the infective copepodid stage. Then the parasites must find new fish hosts or die. The time it takes for sea lice larvae to become copepodids is dependent on water temperature, and their survival is greatly reduced when the salinity is less than 30 parts per thousand (ppt).

There is no evidence that the presence of sea lice in the locations of fish farms is so great that it has caused significant disease or economic loss. Therapeutic compounds approved by authorities for use on fish farms for the control of sea lice are administered either in medicated feeds or by immersion in solution (see Appendix E).

There is an absence of scientific information to demonstrate the risk of cross-infection of sea lice between farmed fish and wild fish. It is known that juvenile fish introduced to grow-out facilities from land-based hatcheries are free of disease agents and become infected from the wild fish reservoir, but the potential for sea lice on farmed fish to increase the background infections on wild fish is uncertain. The emerging picture of sea lice associated with cultured and wild fish in the northeast Pacific suggests that, contrary to some circumstantial reports, there is no basis for expecting an increase in wild fish infections in the immediate vicinity of any source of lice larvae, including those hatched from lice at fish farms. New infections will occur only after the lice have drifted on currents some distance from their source. The distance and larval survival depends on temperature and current speeds. There is also some recent evidence that small estuarine fish, such as common sticklebacks (gasterosteids), act as an important reservoir for sea lice, and these quickly multiply when the salinity of the water increases.

Disease and its transfer are best prevented by good management practices. These include, for example, removing all mortalities daily as these are a potential source of disease, avoiding slaughter products such as blood and viscera returning into the ecosystem, and preventing fish escaping at any time.

In summary, there is low risk for the transfer of disease agents between wild fish and farm fish with subsequent ecological effects, providing:

- veterinarians and pathologists are successful in treating most common fish disease conditions, and can eliminate them,
- the health of farm stocks are maintained by appropriate monitoring and response by management,
- certified disease-free stocks are used by farms at all times,
- escapes are rigorously prevented, but if they occur there is a recovery plan, and
- all regulations concerning the movement of exotic species are strongly enforced.

This biological opinion is probably applicable equally to both biogeographic zones and the epipelagic waters of all three ecosystems where fish rearing in marine enclosures might occur.

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Appendix E: Residual Therapeutants

Risk Hypothesis

Veterinarians prescribe and use a suite of medicines, drugs, disinfectants, and parasiticides to treat health problems of captive marine fauna, as well as chemical agents for disinfection. These therapeutants, as they are called collectively, are administered either by inoculation (which includes both injection and vaccination), orally in the feed, or externally with immersion. The perception is that residues of these therapeutants, however administered, will be taken up by the benthic infauna and epifauna to their detriment, and bioconcentrate up the food chain reducing the resistance to disease of demersal and pelagic fish.

Background Experience

Both cultured and wild fish are susceptible to the same pathogens and the same parasites in the aquatic environment as they are all part of the naturally occurring fauna, but it is a hypothesis that intensive aquaculture conditions increase their prevalence within the farm. Therefore the risk of transmission of pathogens and parasites between wild fish and cultured fish is possibly increased as water moves freely between farm enclosures and the open environment, or when farmed fish escape and intermingle with wild fish.

For disease or infestations to occur, pathogens and parasites require not only a conducive aquatic environment for themselves but also one that is stressful to the host. Fish undergoing stress have increased susceptibility to invasion. Their immune system is overcome, and their health is then impaired. Intensive systems themselves are not the cause of stress among farm fish, as shoaling is invariably part of their natural behavior, but stress can occur when there are abnormal changes in ambient environmental conditions: for example, continuing algal blooms caused by prolonged high water temperatures, or “winter chill” when temperatures may be unseasonably low.

Fish can be vaccinated to prevent disease, and most farm fish are treated successfully to prevent many disease conditions, such as bacterial infections. Therapeutic compounds may be used by fish farms for the control of some diseases and external parasites such as sea lice. These compounds may also be used to prevent the introduction of alien pathogens via live aquatic animals or their live eggs from one area to another for release, propagation, or relaying. One example is the introduction of an ectoparasite (*Gyrodactylus salaris*), which was the result of moving live smolts from Sweden to Norway without adequate treatment and health inspections prior to shipment.

Building the Conceptual Model

Therapeutic compounds emanating from aquaculture activities in the marine environment are of ecological concern. The sources of these compounds from farms are the metabolic products (feces, urine, and skin secretions) of the fish after internal or oral treatments, and the direct release into the environment of immersion waters containing a therapeutant for treatment of a disease or parasitic infestation, or uneaten medicated feed.

The processes and intermediate steps between the sources and the biological end points are few. Compounds used in solution or released in solution contribute directly to the background level of the ecosystem. From there, some will be taken up by planktonic organisms, and some may be adsorbed into the sediment. Those in particulate matter fall directly on the sediment.

Following degradation in microbial and microfaunal processes, some therapeutic compounds may still retain their integrity sufficiently to be toxic to nontarget organisms, or to reduce the immunity of some organisms to disease. There might also be bioaccumulation of some compounds up the food chain.

Analysis and Characterization

The biological end points and their attributes for protection are:

1) the species richness and abundance of the seston and nekton,
2) the species richness and abundance of the infauna and epifauna, and
3) the immune-resistance to disease of some demersal and pelagic fish.

These entities are therefore the focus and structure of the analyses and subsequent risk characterization.

Seston and Nekton

Proximal fauna in the seston and nekton can be exposed to therapeutic compounds released by the emptying of the immersion water following treatment. The effect is sudden and very localized, and of very short duration. They may also be affected by residual compounds in the urine or skin secretions, as these excretions are soluble or easily resuspended.

The effect is best determined with a sessile filter-feeding bivalve marine indicator organism, such as a mussel, suspended independently close to the facility. The EcoTox Database for marine indicator organisms will be the reference point to estimate threshold and toxicity of the respective therapeutic compound, but it is necessary to consider the mode of action of each compound to establish appropriate exposure duration. Some are broken down to inert compounds in minutes or hours and may only be acutely toxic immediately on release. A 96-hour LC50 is appropriate for all therapeutic compounds released from the immersion container, considering the immediate dispersal rate and dilution, and indicates the effects at absolute maximum concentration.

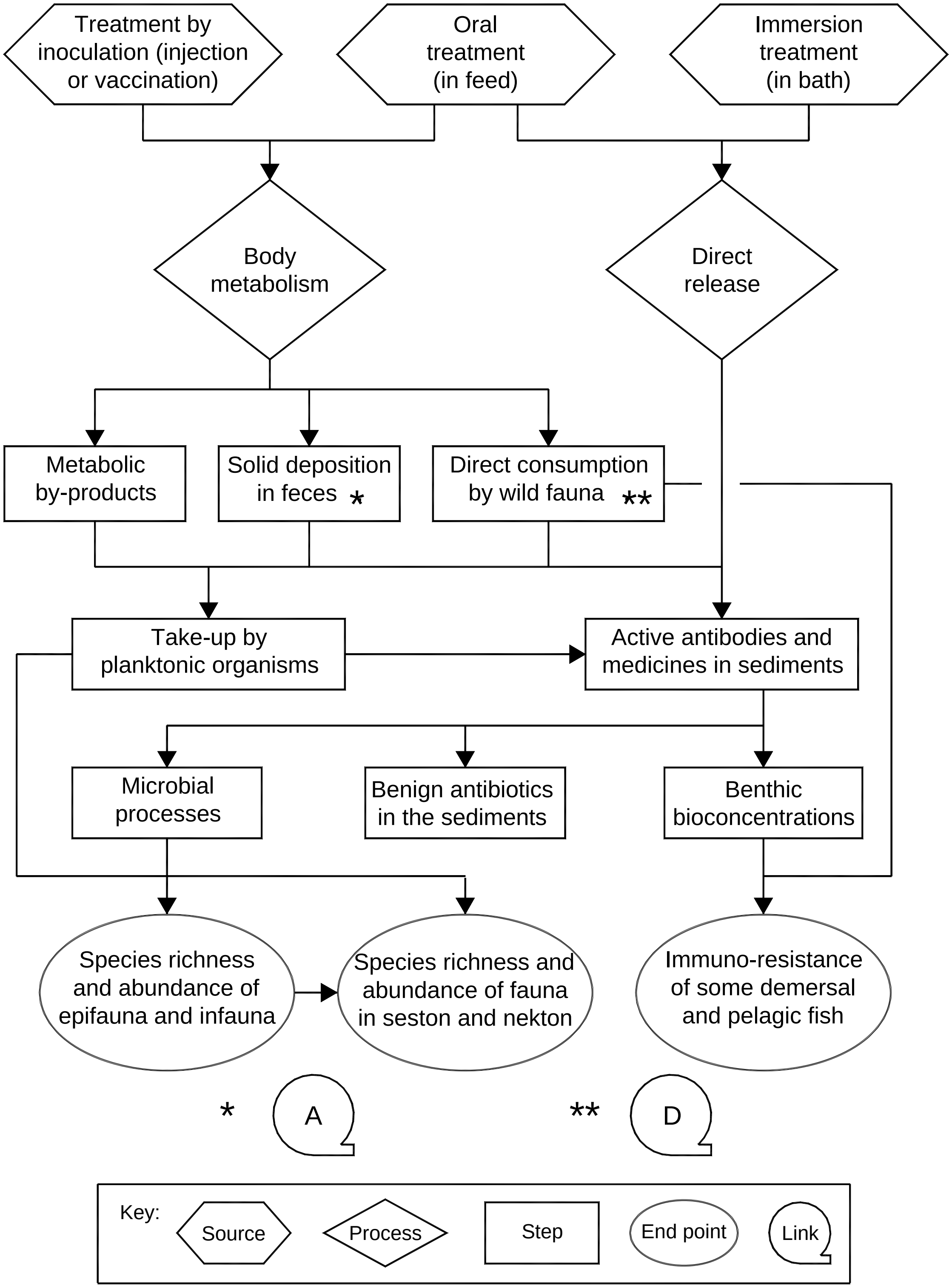

Figure E-1. A conceptual model for residual therapeutants.

With regard to the reasonable worst-case scenario, when many farms in an embayment might be treating an epidemic and releasing immersion waters containing the same or synergistic compounds all about the same time, then reference points will have to be distributed around the embayment and monitored.

Infauna and Epifauna

Proximal infauna and epifauna close to the point of release of immersion treatment waters, or metabolic by-products in solution still containing a residual therapeutant, might be affected. However, they are more likely to be exposed to any therapeutic compound contained in the solid particulate excretory products (feces) of fish metabolism. Exposure will occur mostly within the footprint of farm but possibly dispersed further depending on the qualities of the feces, but the effects can be measured by the same procedures as in the "Seston and Nekton" subsection, above, using an appropriate benthic indicator organism.

In measuring the effect it is important to consider when treated feeds are being used, and their duration of use, as this will affect the rate of accumulation and total concentration in the sediment, as well as the breakdown and mode of action of the respective compound. The effect can be determined by measuring the concentration of the residual compound in the sediment directly, and comparing it with the maximum residual limit (MRL) or permitted residual concentration.

Demersal and Pelagic Fish

The footprint of a farm facility is rich in organic and inorganic matter, and rich in microfaunal and macrofaunal communities. It becomes a feeding ground for both demersal and pelagic fauna, and therefore residual therapeutants may bioconcentrate in the fauna at the higher trophic levels, possibly lowering their immuno-resistance to disease.

For nontarget organisms, such as large epifauna and benthic fish, it is necessary to monitor accumulation continuously by direct analysis for the therapeutants being used. The levels may be influenced by changes in farm production, the age of the fish at the time, and the need (or not) for prophylactic treatment. Monitoring should be performed in both the near field and the far field as crustaceans and fish are free to roam.

Biological Opinion

Therapeutic compounds are not used on a regular basis, but only when pathogenic diseases or parasitic infestations occur, or if, from experience, they might be anticipated if conditions are conducive. Manufacturers also compound and sell medicated feeds in anticipation of certain disease outbreaks, but they too are used only when needed.

Almost every country with an active agriculture sector authorizes the use of therapeutants (veterinary medicines, pharmaceuticals, and vaccines) for cultured fish and shellfish. This they achieve by specific regulations for the manufacturers regarding their quality and efficacy, and specific regulations for their use by veterinarians and farmers. Initially their objective was to protect human health and safety, as these are animals raised for human consumption and the continuous presence of residual drugs may lead to human drug resistance. But protection of the environment is now equally important as therapeutants may continue to affect wild aquatic fauna. For example, parasiticides authorized for the control of host-specific parasitic arthropods, or sea lice, which graze on the skin of many fish, are often broad-spectrum biocides with potential to affect many phyla adversely.

Consequently, the ecological risk from the effects of any therapeutants used in marine fish aquaculture is minimized firstly by using regulated products and in the course of treatment prescribed by the veterinarians. Unfortunately, the respective quality and efficacy of some drugs, and the use of certain medicines, are not standardized around the world. Chloramphenicol, for example, has been banned by many countries from use in all food animals but it is still being used by shrimp producers in some countries.

Secondly, the risk is minimized by application of the most current and efficient treatment. In countries with valuable commercial aquaculture sectors, for example, vaccines have been developed to replace the traditional use of antibiotics. However, this is not the situation worldwide and antibiotics are still used in many hatcheries, although quantities are small, and in countries where vaccines are not readily available.

The possible misuse of therapeutants is being accommodated to some degree by the FAO Code of Conduct for Responsible Aquaculture, and is being enforced indirectly by the food safety and importation requirements of the large seafood markets. Guidelines for their use are becoming an important inclusion in the best management practices recommended for raising individual species. However, best management practices have as yet not been prepared for every farming practice, and they are in the end only nonbinding, honorary agreements, which need not necessarily be observed by every producer, and particularly one facing a disease crisis.

The best solution is disease prevention, rather than cure, and thus reducing the need for therapeutants altogether. Prevention is helped by good site selection in the first place, followed by good husbandry practices. These include, for example, the use of certified disease-free stocks, maintaining sensible stock densities for the age of the population, proper storage and timely use of feed, and effective daily monitoring for mortalities and signs of stress.

In summary, few adverse effects to the marine environment from the presence of therapeutants should be anticipated providing there is:

- only appropriate use of authorized therapeutants,
- a properly managed farm operation preventing disease, and
- the use of certified disease-free stocks.

This biological opinion is probably equally applicable to both biogeographic zones and the epipelagic waters of all three ecosystems where fish rearing in marine enclosures might occur.

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Appendix F: 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* spp. 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

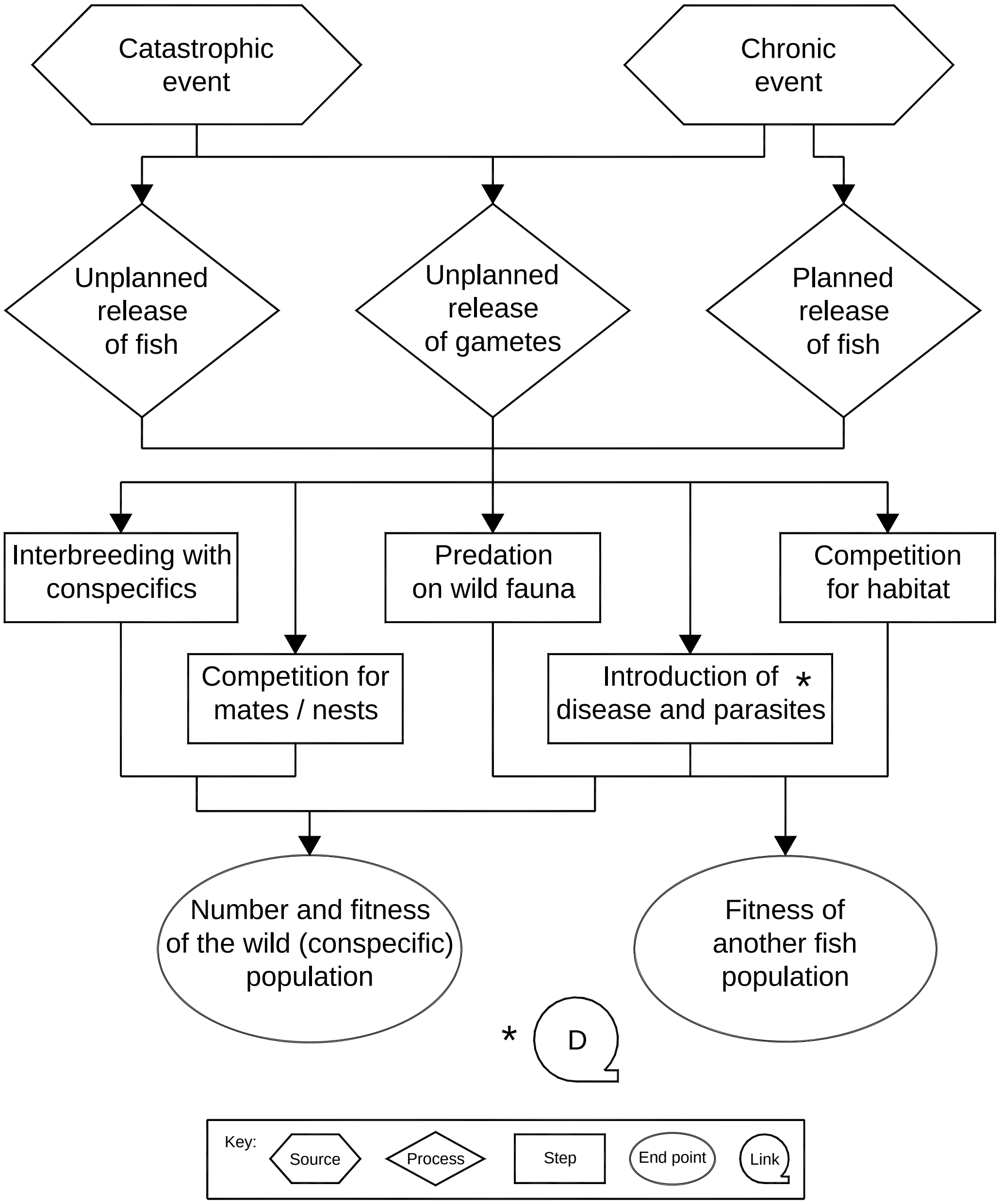

Figure F-1. A conceptual model for biological interaction of escapes with wild populations.

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 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 N_e 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 Atlantic salmon (*Salmo salar*) and Pacific salmon (*Oncorhynchus* spp.), 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.

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Appendix G: Physical Interaction with Marine Wildlife

Risk Hypothesis

Marine aquaculture activities in nearshore and offshore environments are perceived to pose a potential risk to wildlife because the facilities incorporate structures that use nets, ropes, or twine, all of which may be opportunities for their entrapment and entanglement.

Some structures also use surface or underwater lights. These are perceived to pose a risk to the juveniles of migratory fish species, as they might be attracted to the lights and delay their migration, and unnecessarily attract forage fish and predators.

The intensity and frequency of acoustic harassment devices are perceived to be unnecessarily aversive to marine mammals, other than target species, but these are rarely used and are not considered a potential source of risk.

Background Experience

Much wildlife is attracted by marine aquaculture surface structures used for the culture of fish and shellfish. Around structures close to the shoreline, marine mammals and birds are common visitors. Pinnipeds, such as fur seals, true seals, and sea lions, may come to find food, haul-out and rest, and even give birth, while mustelids, such as sea otters and river otters, and predatory and scavenging birds, are more focused visitors coming only for food. For all these visitors, the attraction is not just the chance opportunity of the fish and shellfish being farmed, together with their feed, but the many fish that aggregate in numbers to feed on smaller aquatic animals and plants that colonize around and on the structures. Together, they all create a fertile marine habitat.

Further offshore, the more common wildlife visitors focused on food are predatory elasmobranchs, such as sharks. Then there are visitors by chance, such as whales, porpoises, and migratory marine turtles looking to shelter and rest. Commercial acoustic deterrents have not proved to be effective against any of these visitors, as both animals and birds quickly get used to them, and for the most part they are no longer used or are prohibited by law.

The danger to marine mammals and turtles for entanglement are lines or ropes that are small in diameter, slack in the water, and possibly floating near the surface. Drowning after entrapment in or around a netted structure is a possible cause of loss, together with starvation following entanglement or consumption of discarded or lost debris from a farm, such as a piece of rope or plastic.

Much of the larger marine wildlife visiting aquaculture facilities is protected by international and national conventions. Most countries have regulations requiring that the death of any marine mammal around fish farms is reported, and the information is available on public record.

Building a Conceptual Model

There are a number of physical interfaces of aquaculture facilities and activities on marine wildlife. The specific sources are any floating or submerged structures themselves, any nets, ropes, anchor lines, and anchors associated with any structures, any garbage carelessly lost by a farm, and artificial lighting.

The processes and intermediate steps between the sources and the biological end points are quite direct. In most cases, a large cross section of marine wildlife is attracted to floating or submerged structures. Some colonize, attracting others to take up residence in turn. Marine structures are primarily habitats where food can be found, and a place for rest and shelter. In other cases, wildlife may simply find them to be an obstruction in a migratory pathway or in a breeding area. Thirdly, wildlife not necessarily close to a farm may try to eat or play with garbage that has been lost from a farm. The final result of all these steps is possible entanglement or starvation.

Analysis and Characterization

The biological end points and their attributes for protection are:

1) the lives and safety of marine wildlife, particularly marine mammals, turtles, and sea birds, and
2) the natural habits and target habitats of migratory marine wildlife.

Lives and Safety of Marine Wildlife

The marine wildlife most at risk for their lives and safety are marine mammals. This is because they are more likely to remain around the site for some time, and the effect of their presence around the farm site exposes them to the risk of entanglement in nets and loose ropes. To much less extent there is a slight risk to passing cetaceans, turtles, and sea birds.

Marine mammals are capable of colonizing floating structures in substantial numbers, as marine fish farms are obvious targets not only for the opportunity to haul-out to rest, escape their own predators, and even to give birth, but also because they are potential sources of food. Initially the attraction might have been the farmed fish, but when these prove to be too well protected, marine mammals are prepared to eat any marine fish and shellfish that colonize the new habitat and add to the miniature ecosystem.

Marine turtles, on the other hand, are temporary visitors, attracted by any floating object as a place to shelter and rest. Cetaceans have no reason to visit, and for the most part any interaction is accidental. However, there may be the risk of entanglement in any net or loose

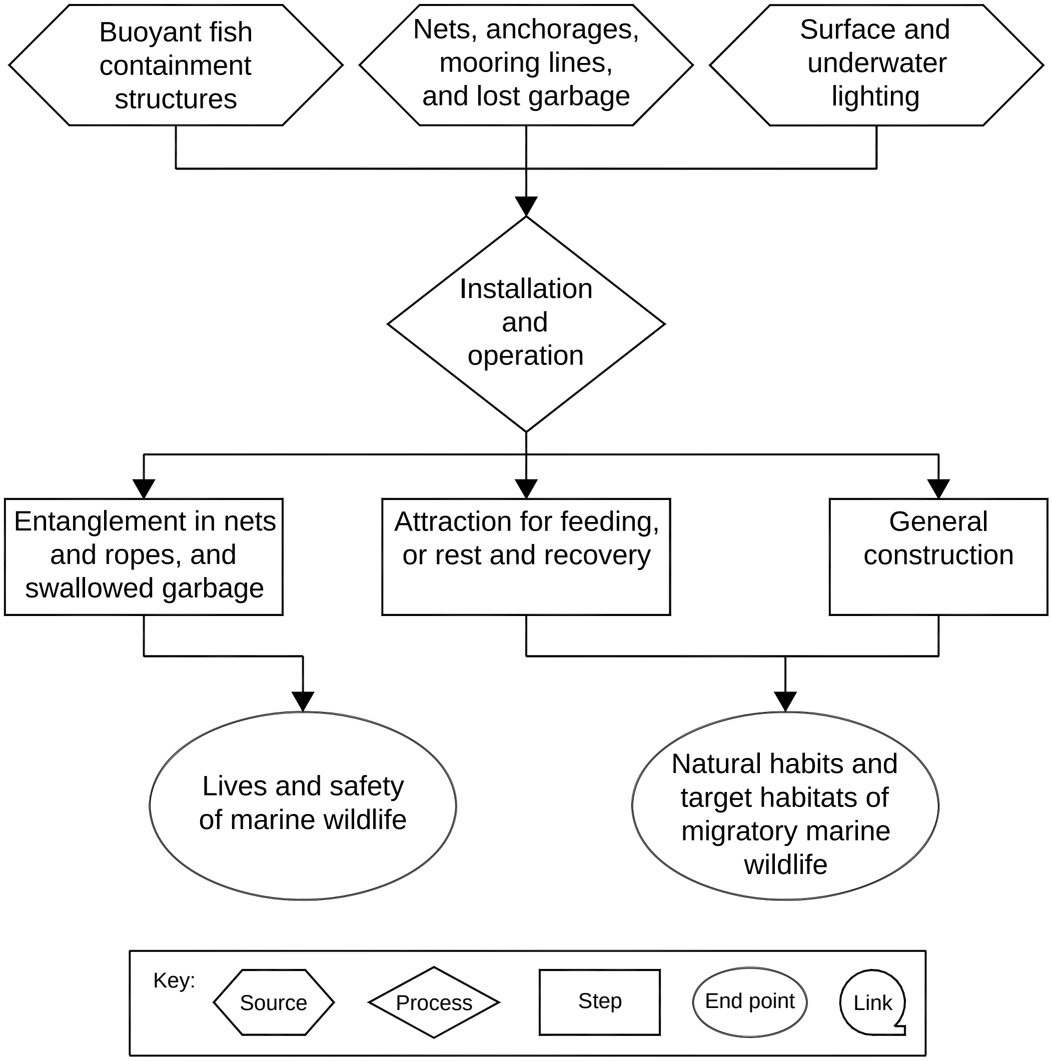

Figure G-1. A conceptual model for physical interaction with marine wildlife.

rope. Both turtles and cetaceans have been known to become entangled in human jetsam, such as lengths of rope and fishing lines, pieces of fishing nets, and swallow indigestible pieces of plastic. Marine aquaculture sites can be a source of similar debris. Most sea birds around marine aquaculture structures are opportunistic scavengers availing themselves of food. The food may be mortalities from the farm, farm fish taken during any transfer or harvest maneuver, or any edible organisms washed off nets and equipment during cleaning. They also consume pelleted fish feed, which may be available at times. But some sea birds are attracted to feed on marine organisms living in the new marine habitat that is created. Here the food is small fish and crustaceans that live in and around the nets, and mollusks that settle on the nets. It is rare for sea birds to become entangled, but it is possible. For the most part, the effect of these interactions on birds is mostly beneficial, but in the long term there might be some effect on their natural behavior.

Effective management can reduce most of these risks, but the effects can only be measured *in situ* by continuous monitoring and recording actual incidents. This process is usually mandatory under the terms of the permit that is issued. Many studies on the population dynamics of several marine mammals, cetaceans, and turtles are already taking place, as are some studies on specific sea birds.

Habitats of Migratory Marine Wildlife

The route of exposure of any physical interaction between marine aquaculture facilities and migratory wildlife, such as cetaceans traveling in pods or individual marine turtles, is simply the existence of aquaculture structures in their migratory pathway, or in their target habitats such as feeding grounds or breeding grounds. Their presence may disrupt the natural patterns of migrants or perhaps make them abandon an area. Individuals might also become entangled in a loose rope or net.

These effects can only be measured by monitoring the population dynamics of the migratory species and their behavior over time, and recording any actual occurrence of entanglement and drowning. Many studies of migratory species already carried out can serve as the baseline for future studies on interactions with aquaculture facilities. Most licenses issued for operating aquaculture facilities require any accidents to marine mammals and turtles to be reported.

For migratory fish, interaction is caused by surface lighting and underwater lights used at certain times of the year to extend the photoperiod for enhancing the growth of farm fish. Young out-migrants move in shoals close to the shoreline at night and are known to be attracted by lights. If they are attracted by the underwater lights of an aquaculture facility, the effect is to delay their migration or possibly to be drawn out into deeper water where they are more susceptible to predators, including perhaps the farm fish in the cages. Forage fish, such as shoals of clupeids, may also be attracted to the underwater lights where they could be consumed by farmed fish or their natural predators. The effect is measurable by a program to analyze the stomach contents of farmed fish throughout the day and during the most appropriate times of year, together with *in situ* research studies during the migration period.

Biological Opinion

The migratory pathways and breeding grounds of cetaceans are often within a few kilometers of shorelines. For the most part, these pathways and breeding grounds are now well known by researchers, and many of the locations have become centers of tourism. It is unlikely that marine fish farmers will choose such a location and, if they should, then it is unlikely that a permit would be provided.

The possibility of a marine mammal being entrapped and drowned in the facilities of a coastal aquaculture site is now extremely low. Modern farm complexes are no longer potential haul-out sites as the surrounding walkways are well fenced, the anti-predator nets are now much stronger, and all net-pen walls are kept rigid and taut. Floating rafts for the production of mussels (*Mytilus* spp.) and oysters (*Ostrea* spp. and *Crassostrea* spp.) are still accessible haul-out sites, but there are no predator nets to entrap them, and the vertical ropes are too thickly covered and heavy to flex and become a trap. Similarly, marine mammals present little or no risk to aquaculture facility operators. The greatest risk to producers of shellfish is fecal contamination by marine mammals, and not direct predation of the stock.

The possibility for a marine turtle drowning within or around a marine aquaculture facility is minimal providing nets and ropes are kept taught.

Modern marine aquaculture facilities do not negatively affect birds. The design of the facilities, including overhead nets to protect the farm crop from birds, prevents almost all adverse physical interactions. On the contrary, modern floating structures provide a habitat that supports many species of birds.

The greatest risk to any marine macrofauna, including birds, is probably garbage from a marine aquaculture site. Waste materials, such as a piece of rope, twine, plastic foam, plastic pipe, feed bags, or similar debris that ends up in the environment as jetsam, is more likely to entangle marine creatures or block their digestive system if eaten by mistake. The way to prevent this is by the enforcement of best management practices by the industry to deal with all potential hazardous waste.

The risk of underwater lighting from net-pen farms directly impacting the out-migration of juvenile fish or attracting forage fish and predators significantly is very low for several reasons. The intensity of underwater lighting is weak to begin with, and is attenuated to 1% within 10–20 m from the perimeter of the net-pen; net-pen complexes are in waters up to 40 m deep, and only larger juveniles would have the opportunity to interact with a complex; and when out-migrations are taking place (usually in the spring and early summer) the use of the lights is fewer than 8 hours, followed by a more than 16-hour interval of natural light, which compels the fish to move on. Finally, there is no quantitative evidence that predators concentrate above normal in areas where there is surface and underwater lighting from structures, or structures themselves. Typically, predators are territorial and only gather if the availability of prey is above average.

In summary, few negative interactions with wildlife from the location of marine aquaculture should be anticipated providing:

- all anchor lines and nets are kept taut at all times,
- predator nets are installed, or the sides of the cages are predator-resistant,
- all garbage and potential garbage is safely stowed until correct disposal, and
- the use of underwater lighting is limited to its necessity.

This biological opinion on wildlife interactions with aquaculture structures, with the exception of underwater lighting, is applicable to both biogeographical zones where fish rearing in marine enclosures might occur, and mostly concerns the epipelagic waters of coastal and offshore ecosystems. The effects of underwater lighting are more important in tropical waters where diurnal variation of light is about equal and attenuation of light is less as there is less particulate matter in suspension.

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Appendix H: Physical Impact on Marine Habitat

Risk Hypothesis

Structures for offshore marine fish aquaculture (which specifically excludes those in the sublittoral coastal zone) are engineered and built to withstand almost all the extreme forces of the open-water, marine environment. The perceived risk is that the anchors required to hold such structures will physically destroy the sea bed habitat, and the large enclosures themselves will have an effect on current circulation and light penetration.

Background Experience

Excluding structures in the sublittoral zone, of which there are many, offshore marine fish aquaculture is currently confined to the continental shelf, which is often defined as lying above the 200-m contour. Because of the capital cost of working in marine waters, offshore fish are farmed intensively, and structures have evolved for specific species and for specific types of site. 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 usually located in sheltered coastal estuaries, sounds, and lagoons that have rapid marine water exchange, and the anchorages are less than 30 m deep. A single circular or rectangular net pen may be 150–200 m^2 in surface area and 7–10 m deep. A long rectangular complex of net-pens may be up to 4,800 m^2 in surface area, with predator nets 10 m deep.

Individual buoyant cages are designed for less-sheltered waters, and submersible conical-shaped cages can be deployed in deeper water to avoid storms. Currently, submersible cages from 3,000–22,000 m^3 in volume are being operated at depths of less than 100 m, and up to 30 km offshore.

Net-pen complexes are moored by many discrete taut legs or lines, depending on their formation and size. Additional lines may moor predator nets. Individual buoyant cages are moored by four discrete lines, which maintain tension all around continuously. Catenary mooring systems are still being tested.

Heavy-drag embedment anchors are used because of their high holding power. Of the three classifications of ocean bottoms (mud or silt, sand, and rock or marl), the preferred substrate is sand for its consistency and high holding power. Mud or silt is also good but can vary in consistency, and rock or marl is poor. Anchors can be bolted into rock and lava to give additional strength to the dead weight, but the practice is very costly.

Fish containment structures are designed to operate in currents up to 90 cm/sec, or about 1.74 knots. Sites with stronger currents are not desirable, as most fish must then expend too much energy maintaining their position in the cage instead of growing.

All marine aquaculture structures are regulated by international maritime laws with regard to navigational lighting.

Building the Conceptual Model

The two sources of physical impact on the offshore marine habitat are the large heavy anchors and the structures containing the fish.

There is a common system for each, namely their installation and operation, and a few intermediate steps. These include the possibility of dragging anchors during heavy seas, a reduction in light penetration, and the reduction in water-mass exchange.

The biological end points and their attributes include, potentially, the reduced abundance of benthic infauna and epifauna, the reduced abundance of sea grasses (*Zostera* spp. and *Phyllospadix* spp.), and the biological diversity of a confined coastal ecosystem.

Analysis and Characterization

The biological end points and their attributes for protection are:

1) the biological diversity of a confined coastal ecosystem;
2) areas of ecological importance, such as sea grasses, kelp beds, coral reef, etc.; and
3) the abundance of benthic infauna and epifauna.

Biological Diversity

Changes and reduction in water-mass exchange can indirectly affect the biological characteristics of confined ecosystems. Indicators of potential change include, for example, reduction in oxygen levels and decreased turbidity, which in turn reduces available nutrients. Changes in water quality in a confined ecosystem close to an aquaculture site can be determined by a standard water quality monitoring program, with spatial and temporal replication. If changes prove to be evident, then this can be followed by a biological monitoring program with selected indicator species.

Areas of Ecological Importance

Reduction in areas of ecological importance, in particular beds of sea grass, could be caused by fish enclosures in epipelagic waters either by reducing light penetration, or by dragging anchor lines.

Spatial and temporal Secchi disc transparency readings at regular intervals are the simplest method for comparing the extinction coefficients of light in and around an aquaculture

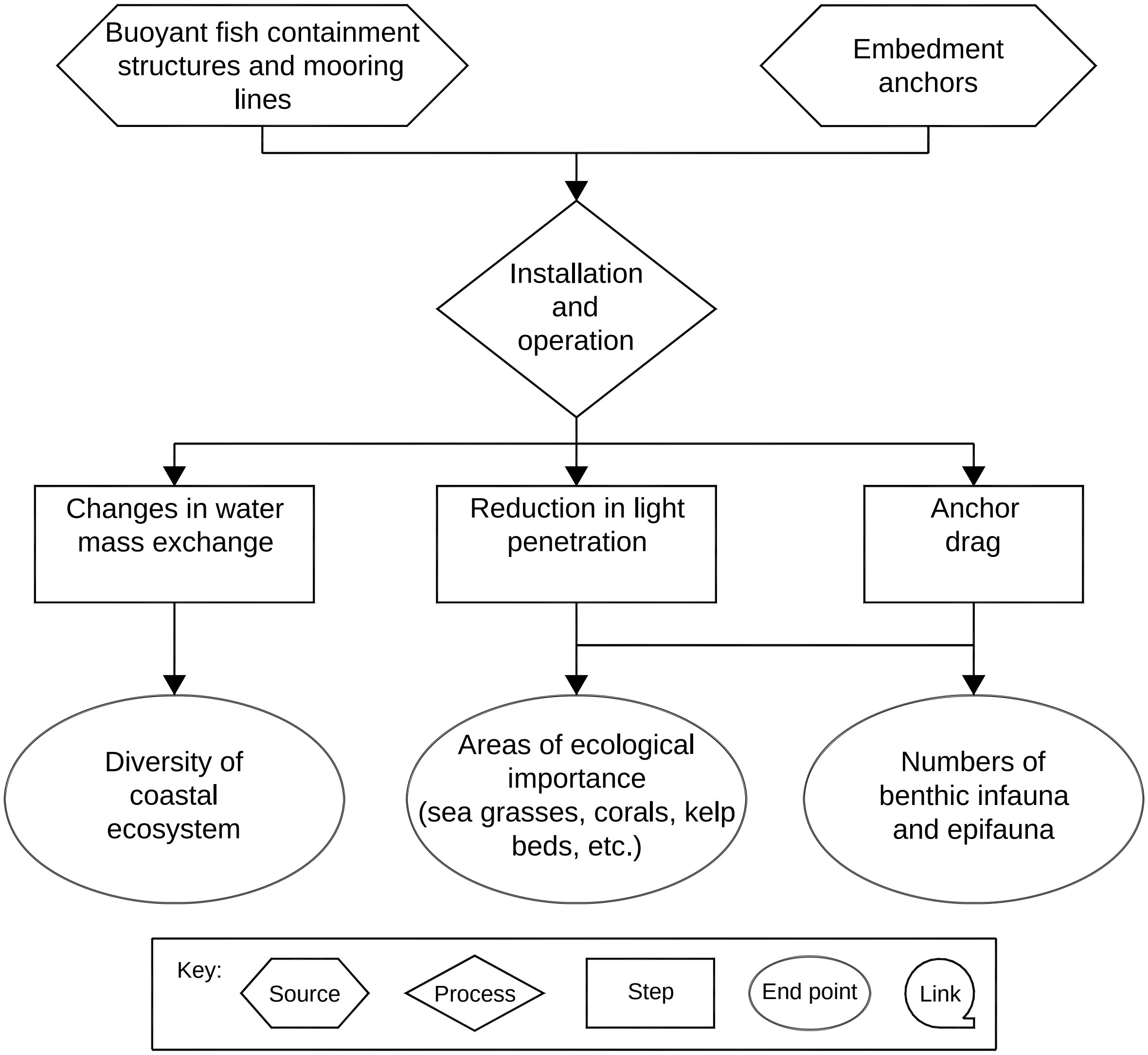

Figure H-1. A conceptual model for the physical impact on marine habitat.

site to determine its effect on light attenuation. Mapping the location and areas of large sea grass beds can be undertaken in a number of sophisticated ways (satellite imagery or underwater video), but for localized effects the traditional quadrant surveys by divers is appropriate. Divers might be used also to determine any chronic effects of the anchors destroying sea grasses, but in most cases the anchors will be too deep and video monitoring would be required.

Abundance of Benthic Fauna

Changes in the abundance of benthic infauna and epifauna may be the effect of dragging anchors. In coastal waters down to 40 m, divers can take standard core samples, which can be quantitatively and qualitatively analyzed in the laboratory. The results can be compared with reference stations located around the site. For deeper waters, grab samples must be used.

Biological Opinion

Floating offshore structures dampen waves by acting as surface breakwaters. However there is no evidence, as measured by levels of oxygen, that a long rectangular complex of net-pens held just below the surface has any affect on the water-mass exchange from one side to the other. Any possible impact on the water-mass exchange would occur if there were many complexes located in a sheltered water body that already had poor circulation and low rate of exchange. If this was the case then sites would not have been located there in the first place.

Buoyant cages are moored individually and are conical in shape, and therefore must provide even less obstruction to water-mass exchange. As these cages are also intended for deep coastal waters, the issue of affecting the water-mass does not arise.

For engineers, beds of kelp or coral reef suggest difficult and costly anchorage systems, and it is probable that a permit to locate an aquaculture site above a sensitive coral reef would never be requested or granted. Consequently, the most important areas of ecological importance for consideration are the many varieties of sea grasses that are rooted in sand. Sea grasses are distributed throughout both temperate and tropical waters, and all support a rich diversity of epifauna and infauna. Their growth is greatly dependent on the availability of light, and consequently the majority of sea grasses are to be found in subtidal habitats and shallow intertidal habitats down to a depth of 10 m or less. However, some species can be found at depths of 50–60 m. Any effects on these sensitive habitats from a reduction in ambient light penetration by the mass of an individual aquaculture structure or structural complex are more likely to occur in temperate waters than tropical waters. Temperate waters already have higher light extinction coefficients and shallower euphotic zones.

In summary, the risk to marine habitat by the deployment of aquaculture structures is typically little and temporary, or none at all. Provided that any structure and its moorings are properly designed by marine engineers for the site selected, and each drag anchor is designed or purchased based on the detailed analysis of the substrate, then it is extremely unlikely that the structure will move once installed. Only during installation, as the drag anchor is being positioned by the anchor chain, may some disturbance take place of beds of sea grasses together with their epifauna and infauna, but it will be minimal and temporary. Here again, the risk can be managed by the use of the right vessel and equipment during deployment, under the supervision of professionals.

Risks to the ecosystem caused by aquaculture structures altering the water-mass exchange of an area are low at best. They can be managed, if necessary, by limiting the sizes of complexes to prevent any breakwater action, and re-siting them regularly to avoid creating a permanent footprint.

The risk of ambient light penetration shading the benthic flora and fauna of the substrate in the footprint of any complex is also minimal. Any effect is more of an issue in temperate waters.

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Appendix I: Using Wild Juveniles for Grow-out

Risk Hypothesis

For centuries, large numbers of juvenile fish shoaling in coastal waters have been harvested by fishermen for bait and by farmers for stocking in fish ponds. The perceived risk is that the collection of these recruits to a wild population of marine fish can cause demographic changes in both the wild population and in other populations in that ecosystem.

Background Experience

Growing-out juveniles of wild freshwater fish populations in captivity for subsistence is part of the culture of many human societies. With the abundance of juveniles of catadromous fish, such as mullets (*Mugil* spp.) and milkfish (*C. chanos*), which congregate in brackish water lagoons to feed, the practice of out-growing provided large volumes of fish which could be preserved and stored, or marketed to others in the coastal communities. For the modern fish farming industry, harvesting wild larvae and juveniles and growing them out on a farm is only an interim measure while the technology is developed for breeding and artificial propagation of juveniles in hatcheries. Today, for example, there is now little or no collection of penaeid marine shrimp larvae as all the important species can be propagated successfully, and no further collection of some marine flatfish, such as plaice (*P. platessa*) and sole (*S. solea*), as the practice is not economical.

Dependable and economic techniques for propagating a number of valuable species, such as tunas, amberjacks and horse mackerels, mullets, and eels, among other species, have yet to developed. Therefore grow-out for market still depends on the collection of juveniles and subadults from the wild populations, which are either schooling in coastal areas to feed, or migrating to feeding grounds or breeding grounds. In most cases the numbers being harvested are being regulated by fisheries managers.

Building the Conceptual Model

The source of risk to a wild population of fish is the harvest of larvae, juveniles in their first year, or subadults migrating to feeding grounds or breeding grounds. The population may be a target species or a nontarget species.

The process of removing large numbers of juveniles from a population through one of several forms of fishing may result in consequences that offset the loss. These effects may be either positive or negative for a number of populations in the ecosystem. The direct and short-term effect of harvesting large numbers of larvae or juveniles from the wild population is that the potential number of adults will be greatly reduced. On the other hand, reducing the numbers of

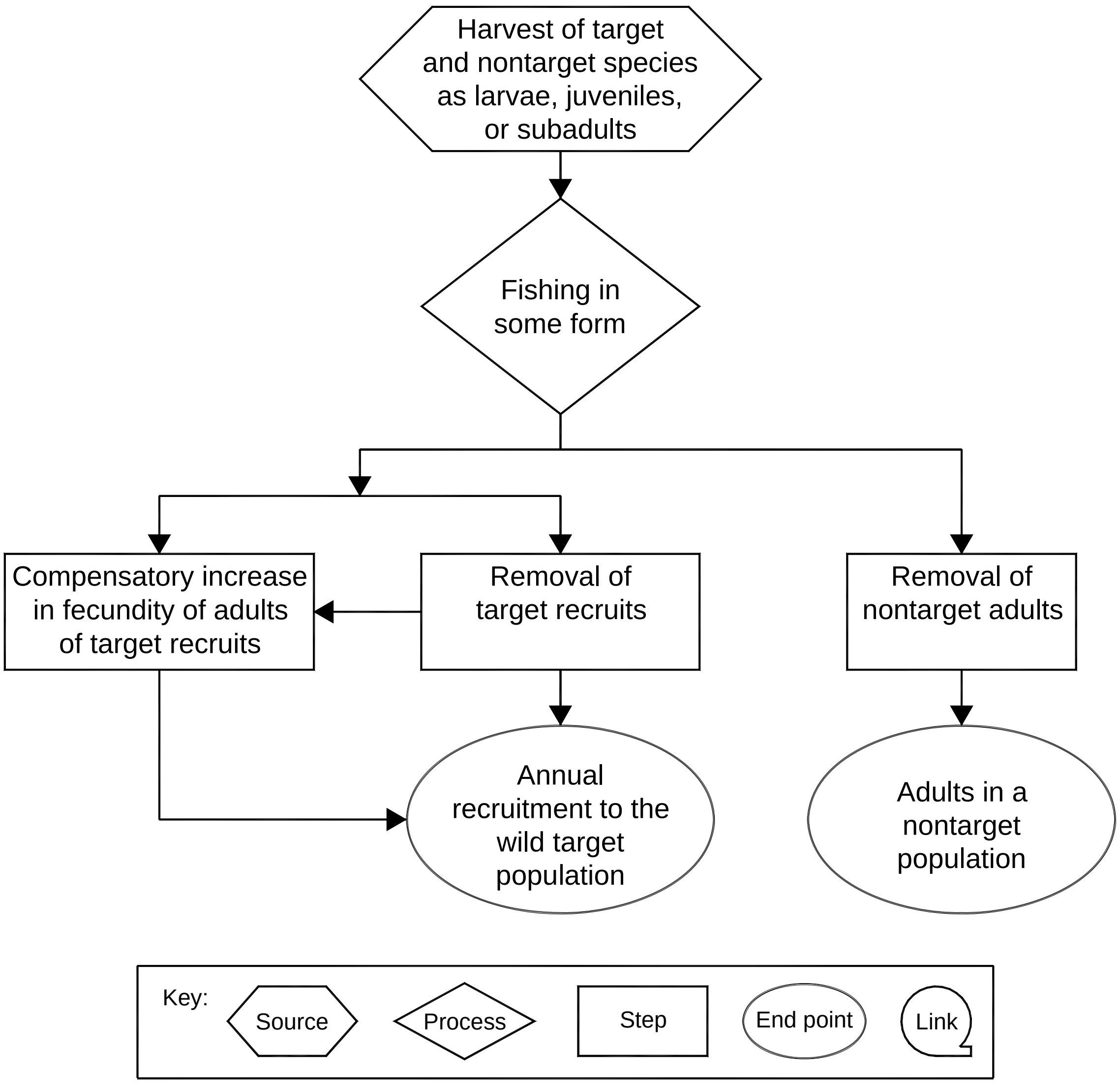

Figure I-1. A conceptual model for using wild juveniles for grow-out.

larvae and juveniles might reduce the competition for food and habitat and therefore improve the quality of those adults that survive. In the long-term, over several generations, the effect of harvesting larvae and juveniles may be a progressive reduction in annual recruitment to the fishery and a decline in total population strength. This could be accompanied by some compensatory behavioral changes, such as an increase in the fecundity of breeding adults.

Analysis and Characterization

The biological end points and their attributes for protection are:

1) annual recruitment to the wild target population, and
2) the adults of nontarget species taken as bycatch.

Annual Recruitment

Estimating any changes in the population dynamics of a fishery to assess the consequences of fishing pressure is a relatively routine procedure for fisheries managers. The accuracy of their assessment, however, increases with the amount and type of information available.

Consequently, monitoring the dynamics of a population of fish to assess the effects of removing larvae or juveniles in large numbers is a long-term process. For shallow coastal habitats, systematic sampling of populations with seine-nets or push-nets at locations spaced uniformly along the shoreline for morphometric data is adequate, but for offshore waters, the sampling program and gear depends greatly on the behavior of the target species. For example, many pelagic fish, such as tuna, have diurnal patterns of distribution with depth and schooling concentration. Concomitant with the sampling of the recruits, it is also necessary to have accurate or estimated information on the relative abundance, age, and size composition of the population, the age at maturity, and mortality rates, as well as relevant information about the habitat.

Armed with this information, fisheries managers can assess the strength of the target population and the structure of its community. They can then decide on a maximum quota of larvae and juveniles that can be harvested annually without jeopardizing the sustainability of the population.

Bycatch

The same techniques for the collection of information are required to assess the impact of harvesting of nontarget species.

Biological Opinion

Juvenile marine fish that school in vast numbers have been harvested from their nursery grounds or on seasonal migrations for stocking and farming in coastal ponds for over two millennia. The most prolific harvests were of young mullets in the Nile Delta and lagoons of the Mediterranean Sea, followed later by some sea breams, sea bass, and eels. Egypt, for example, still collects over 125 million juvenile marine fish annually, of which over 95% are young mullets. There has also been a centuries-long tradition of harvesting many millions of juvenile milkfish in the coastal waters of the Philippines and Indonesia, although in recent years the numbers have declined as the traditional ponds have been converted to marine shrimp production. Within the last 50 years, and with the emergence of the modern aquaculture industry, the practices of harvesting juveniles has been extended to include penaeid marine shrimps in Central and South America, carangids (such as yellowtail and horse mackerel) in Japan, scombroids (such as bluefin tuna) in Australia, and anguillids (eels) and epinephalids (groupers) in Asia.

Harvesting juvenile fish has also been practiced in attempts to improve the commercial fisheries. For example, over a century ago juvenile flatfish were collected from nurseries around the coasts of Europe and transplanted to open shallow waters (sandbanks) in the middle of the North Sea to increase the resources.

The natural mortality of all fauna in the aquatic milieu decreases with age, and therefore the effect of harvesting is numerically less for larvae and juveniles as their chances for survival are low, and only a smaller percentage of the effective breeding population is being removed. This is particularly true for species of fish that school in vast numbers, and these are the species that in fact are harvested and grown out for commercial purposes. However, this is not necessarily a sound reason for fisheries managers to make a judgment because other factors must be considered, not the least of which is coastal development with its continuous reduction in the habitats that are the nurseries for many of these schools.

In summary, the harvesting of larvae, juveniles, and subadults of wild populations for growing out in marine aquaculture facilities presents a low risk of their decrease in the number of adults in both target and nontarget populations. It is possible to harvest a proportion of the young stages of a wild population without detrimental impact. The evidence is in the millions of mullets and milkfish that have been harvested annually for centuries and stocked in coastal fish ponds. In addition, the evidence is that there is little bycatch of nontarget species because most schools are very homogenous. Mullets may be an exception as the schooling populations may contain two or three species, but all of which can be targeted for harvest and grow-out. Consequently, it is the responsibility of fisheries managers to set and justify the limits for the harvest of target species or avoid any unnecessary impact on nontarget species. At the same time it is necessary for aquaculturists to find alternative sources through artificial breeding and propagation.

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Appendix J: Harvesting Industrial Fisheries for Aquaculture Feeds

Risk Hypothesis

There is a perceived risk that the projected global growth of intensive aquaculture, and its dependence on fish meal and fish oils in compounded feeds, will put excessive pressure on the commercial harvest of the industrial fisheries. As these fisheries are an important trophic link in the oceanic food chain, increased fishing effort will impact the sustainability of the resources as well as all carnivorous fauna at the higher trophic levels, such as predatory fishes, marine mammals, and sea birds.

Background Experience

The species most used for reduction to fish meal and oils are the small shoaling pelagic fish harvested from surface waters feeding at the lowest trophic level above or near to nutrient-rich oceanic upwellings. Predominantly these are the clupeid and clupeid-like industrial fishes (such as anchovies, capelin, menhaden, pilchards, sardines, and sardinellas), and sand lances (ammodytids). Their populations are very volatile, as their dynamics and location are dependent on ocean productivity, which in turn depends on the seasonal movement of some deep ocean currents. Consequently, depending on a variety of such biotic and abiotic factors, a population may appear to be at or close to its maximum sustainable exploitation rate.

These large but unstable fisheries are the principal intermediary between oceanic primary production and all the higher levels in the food chain through all the marine ecosystems. As they have a very high content of oils, they are not well-suited to processing for human consumption, and consequently they are reduced into fish meal and fish oils, predominantly for animal and poultry feeds.

The principal constituents of manufactured feeds for farmed carnivorous fish species have been fish meal and fish oils, at levels of about 25% and 30%, respectively. These two ingredients supply essential amino acids and fatty acids required by the fish for normal growth. More recently, small quantities (3–5% and 1–3%, respectively) have been included in feeds for omnivorous and herbivorous fish. In terms of use, manufactured fish feeds account for 30–35% of the fish meal and 50–59% of the fish oils produced annually. Almost all the rest is used in manufactured feeds for terrestrial farm animals and poultry.

Carnivorous fish convert these manufactured feeds to edible flesh with maximum efficiency. Farm salmon, for example, convert approximately one kilogram of feed into one kilogram of fish. For poultry the conversion is 3–5:1, and for swine it is 8:1. For this and other reasons, the farming of carnivorous marine fish is projected to increase substantially as the demand for fish increases beyond the natural resources.

Building the Conceptual Model

The source of the risk is the increased fishing pressure on the shoaling pelagic fisheries low on the marine food chain.

The process is the increasing demand by feed manufacturers for these species to reduce to fish meal and fish oils and compound into poultry and animal feeds, including fish feeds, and in the increasing demand for (oil-rich) seafood by consumers for health reasons. The short-term effect of removing a proportion of this important trophic level in the marine food chain is the reduction in numbers of carnivorous species feeding at the next level; and the long-term effect is the reduction in numbers of the higher fish predators, marine mammals, and marine birds.

Analysis and Characterization

The biological end points and their attributes for protection are:

1) a reduction in the population and breeding potential of the target species, and
2) a reduction in the population strengths of all carnivorous marine species higher up the food chain.

Reduction in Population and Breeding Potential

Because of the economic and social importance of the pelagic industrial fisheries, their population dynamics are now routinely monitored and assessed by fisheries managers and scientists worldwide. Armed with information collected over 50 years or more, fisheries managers predict each year the strength of the target populations. They then decide on a maximum quota that can be harvested without affecting the sustainability of the population.

Reduction in Population Strengths

The same techniques for assessing population strengths have also been applied for many years to species of carnivorous marine fish, marine mammals, and marine birds.

Biological Opinion

Experimental evidence indicates fishing activities can directly or indirectly affect species dependent on them. In the Shetland area of Scotland, for example, a sharp decline in breeding success of the Kittiwake (*Rissa* sp.), a seabird that generally feeds its young almost exclusively on sand eels, has paralleled an intensification of the industrial sand-eel fishery; Stellar sea lion (*Eumetopias jubatus*) populations in the Aleutian Islands have declined by an estimated 68% since the 1970s, possibly due to changes in the availability of preferred prey species that are fished commercially, and the decline of some bluefishes, key predators in western Atlantic fisheries, may be due to the competition with commercial fishermen for squid (*Loligo* spp.), butterfish (*Peprilus* spp.), and Atlantic menhaden (*Brevoortia tyrannus*).

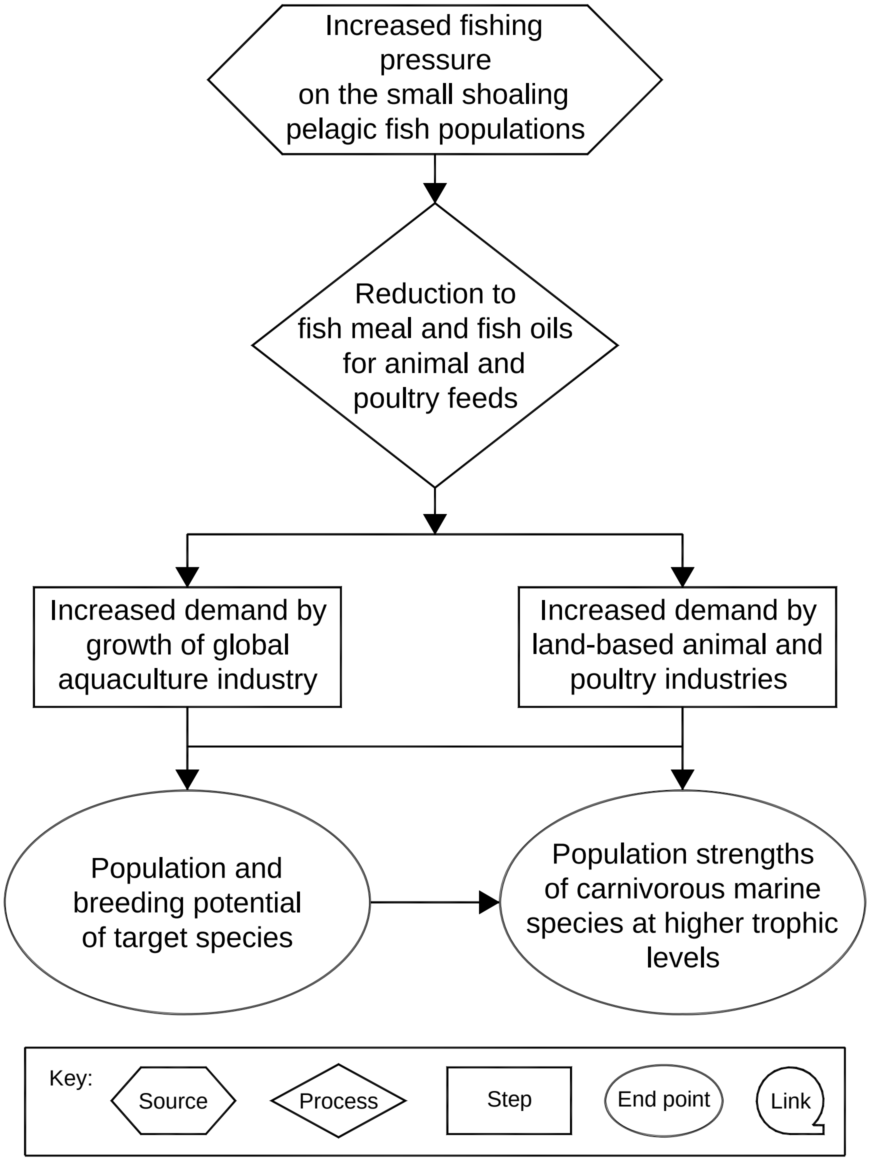

Figure J-1. A conceptual model for harvesting industrial fisheries for aquaculture feeds.

Industrial fisheries for reduction into fish meal and fish oils are an important part of the global harvest, and contribute some 28–33 million mt annually. It is believed that a number of their individual resources have reached their maximum sustainable exploitation rates. As it is well known that these fisheries are important food sources for oceanic fauna at the higher trophic levels, they have been managed specifically by the six major nations involved and there is an international organization of fish meal and fish oil producers that has consultative status with FAO, the European Union, World Bank, and Codex Alimentarius.

There has been intensive research and development by major feed companies and academic institutions to reduce pressure on stocks of pelagic fish traditionally used for the manufacture of fish meal and fish oils to find alternatives sources, such as fish processing waste (trimmings) and use of bycatch not currently landed for economic or regulatory reasons. In 1994, for example, annual discards at sea totaled 17.9–39.5 million mt, compared with 33 million mt of feed-grade fish harvested for reduction. More recent estimates of 20 million mt is equivalent to 25% of the reported annual harvest by marine capture fisheries. More importantly, there has been research to substitute grains and oilseed meals for fish meal as sources of protein and energy, and the development of cost-effective feeds that maximize growth rate, improve the conversion efficiency of feed to flesh, and reduce or eliminate feed wastage.

A distinct advantage of substituting a large part of fish meal and fish oils with vegetable oils in fish feeds is that it will remove most of the toxicants, such as dioxins, which are found in these pelagic fisheries. These then bioconcentrate up the food chain and can be detected in carnivorous fish, marine mammals, and sea birds, as well as farmed fish.

In summary, the projected growth of marine fish aquaculture presents little risk to the small pelagic industrial fisheries unless fisheries managers agree to target new resources in response to demand and rising prices of fish meals and fish oils. Moreover, even partial substitution of fish meal and fish oils in aquatic-animal feeds with suitable alternatives may not result in any significant reduction in the global harvest of industrial fisheries. It would reduce their costs, however, on the world market, which would be reflected in the reduced annual incomes of those communities dependent on industrial fisheries, and a possible increase in fishing effort to compensate.

Assessing and managing the risk is the responsibility of fisheries managers in the countries concerned to set and justify the limits for the harvest of target species and to avoid any unnecessary impact on nontarget species. At the same time, the feed technologists and manufacturers must be encouraged to continue to their research on substituting these ingredients as the demand for animal meats, including fish, continues to grow with the increase in world population.

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