

A Biosafety Approach to Addressing Risks Posed by Aquaculture Escapees

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Abstract

Aquaculture operations should include a comprehensive biosafety program because of the risks they may impose on biological resources in the environments into which cultured organisms may escape. Risk assessment incorporates hazard identification and risk analysis. Risk analysis encompasses describing the likelihood that a hazard and its consequences will occur and the severity of realization of a consequence. For aquaculture, four hazards have been identified: escapes of alien species, escapes of alien species that can hybridize with native species, escapes of cultured stocks into populations of the same species, and escapes of genetically engineered organisms. Consequences of the realization of these hazards may affect multiple levels of biodiversity, from genes to populations to communities. For escapes of cultured organisms, possible consequences and their likelihoods are described, along with the consequences that may range from extinction of native species to erosion of genetic diversity among populations. A complete risk management program includes developing risk reduction measures and a monitoring program to determine if such measures are adequate. Monitoring aquaculture operations to detect escapees and their ecological impacts makes it possible to: (i) detect the occurrence of a hazard and initiate remedial efforts to reduce its occurrence and minimize adverse consequences; and (ii) learn more about a given cultured stock's likelihood of imposing consequences, which can then be applied to the risk analysis of other aquaculture operations. Including all these elements in biosafety programs will lead to systematic evaluation and solid evidence of the degree of ecological safety versus risk of an aquaculture operation, as well as encourage adaptive mid-course corrections in existing biosafety measures and adaptive learning that will improve future biosafety decisions and measures.

Introduction

Aquaculture is an important source of food, employment, and revenue for many countries and communities. Starting in the 1950s, worldwide aquaculture production has increased at rates exceeding 5 per cent annually, and in recent years the annual increase has been more than 10 per cent (FAO 2000). Although the contribution of African aquaculture to global production has been low so far, it is expected to play an important role in the years to come to meet the increasing demands. Yet even though aquaculture shows promise for providing local and regional economic benefits in Africa, certain aquaculture systems and practices may also pose threats to the environment that, in turn,

would undermine local communities' options for achieving sustainable livelihoods. Escapes of cultured alien species, selected or domesticated broodstocks, and transgenic organisms (genetically engineered organisms), in some cases, could adversely affect aquatic biological diversity, ranging from the genetic resources of extant native wild populations to ecological resilience of fish communities.

The paper addresses methods for assessing and managing ecological risks posed by escapes of cultured fish. First, the components of a comprehensive biosafety program are reviewed and then these components are applied to fish that might escape from an aquaculture operation. Such a comprehensive biosafety program has risk

assessment and risk management components (Table 1) (Kapusinski et al. 2001).

Risk Assessment

Risk assessment includes identifying hazards that denote events that could pose harmful consequences and quantifying risk that denotes the probability of a hazard occurring. Hazard identification is important because the rest of the risk analysis and management procedures depend on it. A full risk analysis goes beyond assessing the probabilities of hazards occurring. The next key tasks are to determine the consequences of realization of a hazard and the severity of these consequences. For aquaculture, these consequences may be economic or social, as well as biological. Thus social acceptance of risk decisions depends on explicit deliberation of different perspectives (Committee on Risk Characterization 1996; Nowotny et al. 2001). Evaluating severity will be a value-laden process. The Royal Society of London (1992), for example, characterized risk assessment as identifying hazards, quantifying them, and allowing for values and perceptions of risk. Severity will also be affected by the extent to which feasible options exist for mitigating the hazard. For example, the extirpation of a population may eliminate a valuable fishery in the short-term. However, if the species has nearby populations that can

recolonize the system in the long run, loss of the local population will be less severe than the extirpation of the last population of a species.

The risk assessment can be summarized as a matrix of likelihood plotted against severity of consequence (Figure 1). Clearly, great effort should be made to avoid hazards with a high probability of occurrence and most severe consequences (Figure 1, upper right corner). The second level of priority regarding the three remaining cells in Figure 1 is harder to set and requires an answer to the question, "should we address low probability hazards of high severity or high probability hazards with less severe consequences?" The answer should be reached through deliberation among legitimate representatives of all potentially affected parties. Finally, scientists and other relevant technical experts should judge the certainty of the knowledge used for the analysis in order to prioritize risk reduction measures, and identify information required to complete a full risk assessment.

Risk Management

Risk management involves planning and implementing risk reduction measures and monitoring to determine if the risk reduction is working. Risk reduction measures can either reduce a hazard's likelihood of occurrence or reduce the severity of its consequences. Monitoring projects

Table 1. Systematic steps of risk assessment and management, essential but not sufficient parts of an analytic deliberative framework of risk characterization and decision-making (modified from Kapuscinski et al. 2001).

Step in risk assessment and management	Key question addressed at this step
Hazard identification	What event posing harmful consequences could occur?
Risk analysis	How likely is the hazard? What would be the consequences of the hazard and how severe are they? What is the risk assessment, i.e., a matrix of likelihood plotted against severity of consequence? Each cell of the matrix should be accompanied by a qualitative assessment of the response and level of assurance needed to reduce harm if the cell's conditions were to occur. How certain is the knowledge used to identify the hazard, estimate its likelihood, and predict consequences?
Risk reduction planning and implementation	What can be done to reduce risk, either by reducing the likelihood or mitigating the consequences of hazard realization?
Risk tracking (monitoring)	How effective are the implemented measures for risk reduction. Are they as good, better or worse than planned for? What follow-up / corrective action / intervention will be pursued if findings are unacceptable? Did the intervention adequately resolve the concern(s)?

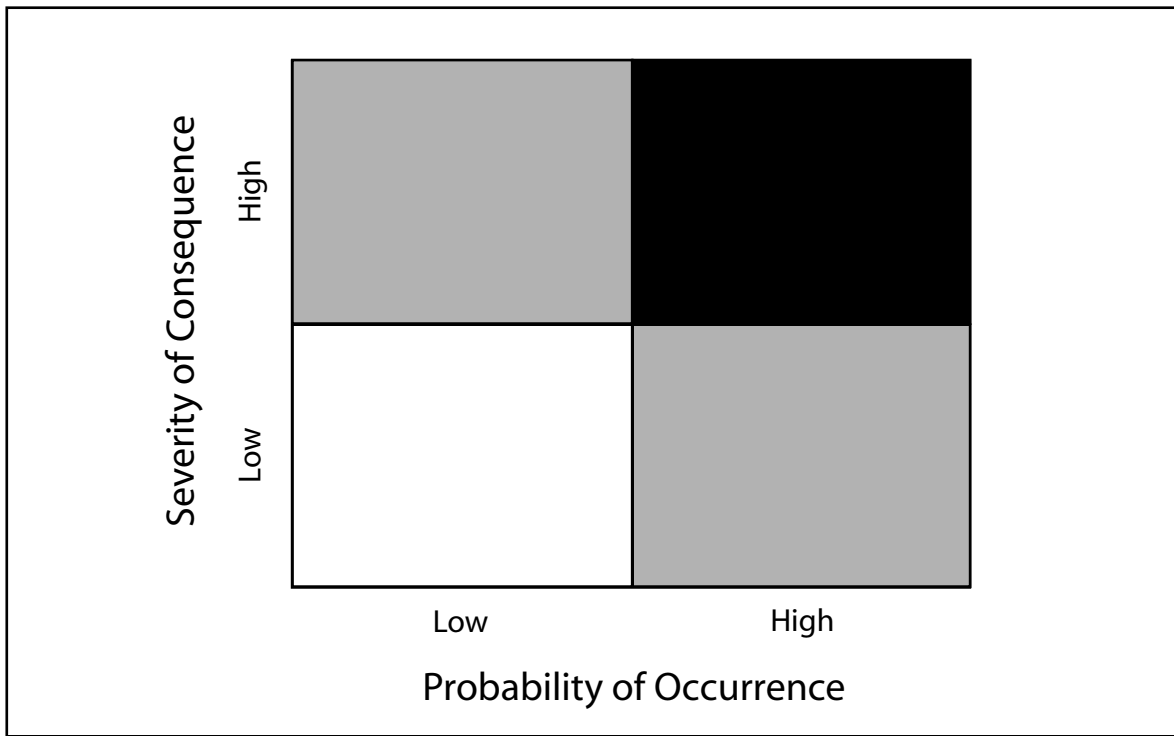


Figure 1. Schematic of a risk assessment matrix. Hazards of greatest concern are those with high probability of occurrence and high severity of consequences (black area). Social and economic considerations will influence the priority given to hazards in the gray area. Depending on the quality of information available, the axes could be continuous values or more refined categories (for example a 3 x 3 matrix of high-medium-low rankings).

that move forward based on risk decision-making is the only way to achieve adaptive improvements in future risk assessment and management. Monitoring can be used to detect the occurrence of hazards and signal the need for either stopping, revising, or mitigating current practices. In this role, it is important to conduct monitoring at a point early enough in the process to allow for effective remedial actions. The realization of certain hazards rules out any possibility of mitigation. In this situation, monitoring may provide information about the severity of consequences that can be used for improved future risk analyses of similar situations.

Who Participates in Biosafety Programs?

The history of safety programs for technologies whose products offer clear societal benefits, but also pose public harm has demonstrated the need for safety programs to be, as Gibbons (1999) would say, “both scientifically reliable and socially robust” (Kapuscinski et al. 2001). Good science, therefore, is necessary and indispensable, but not sufficient for establishing credible and effective biosafety programs addressing various environmental concerns in aquaculture. A broad

cross-section of potentially affected and interested parties needs to collectively deliberate on key elements of biosafety programs (Committee on Risk Characterization 1996; Kapuscinski et al. 1999).

The most durable way to achieve broad participation and support is to develop biosafety programs through an iterative analytic-deliberative process (Committee on Risk Characterization 1996; Kapuscinski 2001). Analysis uses scientifically reliable methods to arrive at answers to factual questions (for example, the questions listed for risk analysis in Table 1). Inter-disciplinary teams of scientists, scientific studies, and tools designed to assist risk decision making (for example, Agricultural Biotechnology Research Advisory Committee 1995; Brister and Kapuscinski 2002; Scientists’ Working Group on Biosafety 1998) play the dominant role in analysis. Deliberation uses processes such as discussion, reflection and persuasion to communicate, raise and collectively consider issues, increase understanding, and arrive at substantive decisions.

Public officials, scientists, and potentially affected and interested parties participate through

iterations of analysis and deliberation. For the issues addressed in this paper, potentially affected and interested parties might include: local farmers interested in introducing a new genetic variety or new species of fish into their farms; local subsistence, recreational and commercial fishers; public officials responsible for governing aquaculture, fisheries and other aquatic natural resources; and fisheries scientists with expertise in population genetics, conservation biology, fish population dynamics, and aquatic ecology. They may also include other people whose livelihoods depend directly or indirectly on healthy fish communities in the water bodies they customarily access. Such a broad cross-section of parties should first deliberate on problem formulation, i.e., defining what events they agree are “hazards” and what possible outcomes they agree are “harmful consequences”, as well as criteria for determining the “severity” of a consequence. Analysis of scientific principles and evidence, as laid out in this paper, provides an essential point of departure for these deliberations. Broader deliberation on problem formulation, however, is equally essential in order to assure that all affected parties will accept and abide by the ultimate risk and safety decisions. It is likewise important to link scientific analysis and cross-sectoral deliberation in designing, reviewing, and updating (based on new information) all components of a biosafety program outlined in Table 1. For example, if these different parties first deliberate to reach agreement on acceptable versus unacceptable levels of the likelihood of different risks, then they are more likely to reach durable agreement on risk reduction and mitigation measures and to pro-actively help implement such measures.

In what follows, the paper outlines the essential components of a risk assessment and management program for aquaculture of alien species and genetically enhanced broodstocks. First four types of hazards associated with the escape or intentional introduction of organisms from an aquaculture facility are identified. Then a range of possible consequences, with an emphasis on ecological results, and ways of determining their likelihood of occurrence are discussed. Risk management involves risk reduction and monitoring. Several approaches to reducing risk from aquaculture escapees, either by minimizing the likelihood or mitigating the consequences are suggested. Finally, concluded with a discussion of monitoring that may be used to detect escaped organisms or to evaluate the severity of consequences due to their escape.

Risk Assessment for Escapes of Alien Species and Genetically Enhanced Broodstocks

The types of hazards imposed and the potential consequences to aquatic resources depend on the species cultured and the species present in the environment in which cultured species might escape or be stocked. Ideally, one should begin a risk analysis at an early point in the planning of an aquaculture operation because the choice of species and facilities will affect the likelihood of escapes at the outset. For discussion purposes, however, the paper begins with an analysis of risks at the point of escape (or stocking) of the cultured species. Four types of hazards imposed by cultured organisms are distinguished and the risks and consequences of these hazards are discussed.

Hazard Identification

The types of hazards imposed and the potential consequences to aquatic resources depend on the species cultured and the species present in the environment into which cultured species might escape or be stocked. The escape of an alien species with no close relatives with which to hybridize (Hazard I) may impose drastic effects on aquatic communities. Although aliens will impose no direct genetic consequences through interbreeding, they may act indirectly on genetic resources by reducing the abundance of another species, even to the point of extirpation. The escape of aliens that have close relatives with which they can hybridize (Hazard II) may impose the same consequences as aliens without relatives, with the addition of direct genetic consequences through interbreeding. The escape of aquaculture strain of native species into environments harboring populations of the same species (Hazard III) may alter the genetic diversity and fitness of the wild population. Finally, the escape of genetically engineered organisms (Hazard IV), which may fit into any of the hazards above, introduces additional concerns that merit attention.

Risk Analysis

Hazard I: Escape of alien species - invasion without hybridization

The ecological consequences of invasive alien species (Hazard I) may range from integration into the local community with few observable effects to extirpation of native species (Moyle and Light 1999). In between these extremes are

cases where alien invasions alter the abundance or behavior of species in the invaded community. For instance, Lever (1996) reviewed the impacts of tilapia species introduced throughout the world and found that ecological consequences included extirpation of native species, numerical domination of fish communities, and alteration of water quality and aquatic vegetation that indirectly affects many other parts of the community.

The risk of an alien species invasion causing harm is the product of two components: the likelihood that an alien species will become established, multiplied by the likelihood that an adverse consequence will occur if it does become established. Invasions of alien species have been the foci of much empirical and theoretical interest (Moyle and Light 1999; Parker et al. 1999; Williams and Meffe 2000), including the role of aquaculture as a “gateway for alien species” (Naylor et al. 2001). Unfortunately, this work shows that it is difficult to predict the likelihood of invasion by a specific species into a given environment, and even more difficult to predict the consequences of an invasion. Nevertheless, a careful evaluation of the characteristics of the species and the potential receiving environment will aid in assessing the risks of the alien species. In addition, the history of the species’ success as an invader elsewhere (for example Lever 1996; Bartley et al. 1998) will suggest its likely invasiveness potential.

Hazard II: Escape of alien species – with possibility of hybridization

The consequences of alien species escaping into waters with wild relatives are similar to those posed by Hazard I. However, Hazard II can lead to additional genetic alterations of populations of native species through hybridization. If escapees are capable of interbreeding with native species and producing viable hybrid descendants, introgressive hybridization can result in a complete loss of the uniqueness of the gene pool of a population, subspecies or species, resulting in a “hybrid swam”. The loss of this level of genetic diversity may reduce the evolutionary potential and thus the long-term existence of the native populations, as well as reduce options for aquaculture breeding programs that depend upon the local gene pools. In extreme cases, a native species gene pool will be replaced by alien or hybrid genetic materials, thus leading to extinction of a species (Scribner 2001, and

citations therein). For some species, genetic intermixing may not continue into advanced generations because of sterility or low fitness of hybrids. Over time, natural selection should remove many of the alien genes in the population. Interbreeding, however, will result in the “wasting of reproductive efforts” of native species when they contribute to offspring exhibiting reduced fitness.

Risks due to hybridization are a product of the likelihood of interbreeding between aquaculture escapees and native populations, and the likelihood of the consequences described above. Determination of the likelihood of gene flow from aquaculture populations to native fish populations requires information about life histories, especially reproductive biology (for example behavior and timing) and spawning habitat use, for both aquaculture species and closely-related species in the wild. Natural hybridization among fish in closely related taxa is relatively common because of external fertilization, weak behavioral reproductive mechanisms, unequal abundance of two parental species, competition for limited spawning habitats, and secondary contact of recently evolved species. Campton (1987) and Lowe-McConnell (2000) reviewed a number of cases where tilapia species hybridize when stocked together in an aquatic system. The likelihood of hybridization may also fluctuate over time due to the changing demographics of aquaculture and native fish populations. For example, if the number of escaped individuals, either introduced species or interspecific hybrids, overwhelms the number of native fish species, the native fish may interbreed with escapees at higher frequencies due to higher encounter rates even if they prefer to mate with conspecific counterparts.

Hazard III: Escape of aquaculture strain of native species into environments with populations of the same species

The consequences of escaping native species will depend in part on the genetic differences between the escaping strains and the wild population. Most fish species, especially in fragmented and isolated freshwater systems, are made of multiple populations with varying levels of genetic differentiation among them. For example, growth traits (partly genetically controlled) differed for strains of *Oreochromis niloticus* from various parts of Africa (Penman and McAndrew

2000; Seyoum and Kornfield 1992). They could distinguish the seven subspecies of *O. niloticus* using molecular genetic markers. There are two possible consequences of aquaculture escapees interbreeding with genetically-structured natural populations: firstly, homogenization of genetic differences between populations that might reduce the long-term persistence of natural populations; and secondly, outbreeding depression, a reduction in fitness and thus productivity of offspring from parents that are genetically dissimilar. In addition, domestication of aquaculture stocks necessarily causes genetic changes in them that can contribute to a decline in fitness upon intermating with wild populations (see Waples 1995 for a review of the genetic basis for outbreeding depression in wild fish populations).

The risk imposed by escapes of cultured fish of a native species is the product of the probability of escapees replacing or interbreeding with wild fish multiplied by the probability of the two consequences, loss of evolutionarily important genetic differences among populations, and outbreeding depression. The probability of interbreeding by escaped fish will depend on their entry potential (for example frequency of escapes at different seasons, and distance to area with wild populations) and the introgression potential (for example survival to reproductive stage; similarity in reproductive development; timing of spawning and mating behavior of cultured and wild fish; and survival of offspring). In many cases, one can assume that the aquaculture escapees will interbreed, and thus directly interact genetically with wild populations. Risk analysis then focuses on the probability of realizing negative consequences of intermating.

The probability of negative consequences due to interbreeding of cultured strains and wild populations of a native species increases as genetic differences between the cultured and wild groups increase. Greater differences arise from longer and more complete isolation between populations and from more strongly discordant selective pressures in different environments. An aquaculture broodstock and a wild population may differ genetically because the broodstock derives from a non-local population that is genetically different from the one in the local environment (i.e., has evolved separately) or because of genetic changes in the aquaculture environment (i.e., random change due to genetic drift or selective differences between the aquaculture and natural

environment). The probability of negative consequences can be reduced if the cultured stock is derived from a local population, and thus has a similar genetic background. Cultured organisms, however, will become domesticated as selective forces genetically adapt them to the aquaculture environment. As domestication increases, adaptation to the natural environment decreases, raising the likelihood of outbreeding depression even if the wild population was the founding source for the aquaculture broodstock.

Hazard IV: Transgenic organisms (genetically engineered organisms)

Transgenic fish represent special cases of Hazards I-III, and thus their escape from aquaculture facilities may lead to the consequences of aquaculture escapes described above. Of importance to risk analysis of transgenic escapees is whether or not the novel traits they express alter the probability or severity of consequences they might impose on natural populations. To determine this, risk analysis of transgenics requires evaluation of the net fitness of transgenic escapees.

Net Fitness: The term net fitness is scientific shorthand for the degree to which an organism succeeds at passing on its genes to future generations. Net fitness is fully determined by the joint effect of six fitness traits of the organism: juvenile and adult viability (chances of surviving to sexual maturity and surviving to procreate additional times), fecundity (number of eggs produced by a female), fertility (per cent of eggs successfully fertilized by male sperm), mating success, and age at sexual maturity (Muir and Howard 2001a). The notion that survival alone determines the spread of transgenes - hence transgenic organisms exhibiting reduced survival always pose no environmental hazard - is wrong; the likelihood and degree of transgene spread following an escape from an aquaculture facility depends on the net effect of all six fitness traits (Muir and Howard 2001; Rodriguez-Clark and Rodriguez 2001).

Transgenic Alien Species Invasion: Alien species invasion is a possible consequence if transgenic fish enter a suitable ecosystem that lacks wild relatives. Fertile transgenic fish are likely to establish a self-regenerating population of the alien species if their invasive ability, as a direct or indirect effect of their engineered genes, is greater than or equal to that of the unmodified invasive

parental species. One major indicator is if the net fitness of the transgenic fish line is equal to or greater than that of the unmodified parental line. An example of a transgenic fish with a novel trait that might alter net fitness is a line of goldfish with antifreeze protein transgenes giving them increased cold tolerance (Wang et al. 1995). Large-scale production of such goldfish would raise the possibility that they would greatly increase the range of water bodies invaded by this goldfish, already an established alien in some inland waters, and, through their prolific breeding and hardy nature, become a greater nuisance.

Gene Flow from Transgenics to Wild Relatives: Gene flow is a potential consequence if fertile transgenic fish enter water bodies with wild relatives of the same or related species and interbreed with wild relatives. Recently published research suggests three plausible scenarios of gene flow (Muir and Howard 2001, 2001a). In a purging scenario, the net fitness of a transgenic fish is much lower than that of its wild relatives and natural selection quickly purges any transgenes inherited by wild relatives. This is the safest scenario in that it does not pose adverse environmental consequences. In a spread scenario, gene flow would lead to spread and persistence of the modified trait in the wild population if the transgenic fish have equal or higher net fitness than their wild relatives. Recent studies suggest that age at sexual maturity has the greatest effect on net fitness (and thus transgene spread), followed by juvenile viability, mating advantage, female fecundity, and male fertility (Muir and Howard 2001; Rodriguez-Clark and Rodriguez 2001). For example, transgenic fish with greatly reduced viability but with an earlier age at sexual maturity or sufficiently fitness-enhancing changes in other fitness components could still spread their transgenes. The spread scenario may lead to the displacement of the wild population by descendants of the transgenic escapees. Alternatively, temporary spread of a transgene may lead to a surprising third outcome, the “Trojan gene” scenario.

If a transgenic fish line exhibits both a large mating advantage and a moderate viability disadvantage compared to wild relatives, but the large mating advantage overwhelms the viability disadvantage, recent research predicts a dramatic outcome of gene flow. The mating advantage drives the transgenes into the wild population, spreading them rapidly throughout the population, but the lower survival of each consecutive generation carrying the transgenes

eats away at the population size. Research predicts that this “Trojan gene effect” would trigger a rapid decline of the wild population (Muir and Howard 1999, 2001). Unless the decline is stemmed by human intervention or by sufficiently strong, counteracting natural selection, the wild population will become extinct. Other scenarios can be envisioned in which trade-offs among the fitness component could lead to “Trojan gene” effects.

Risk Reduction

Risk reduction planning and implementation comes into play whenever hazard identification and risk analysis have led to the conclusion that escapes of organisms from aquaculture operations will impose an unacceptably high likelihood of a particular hazard multiplied by the severity of possible consequences. The first decision to make in risk reduction planning is whether to aim for reduction or mitigation of each risk at issue. Mitigation differs substantially from risk reduction in that it simply accepts the risk and focuses on designing measures to compensate for the harmful consequences. Reduction, in contrast, does not accept risk wholesale, but rather focuses on managing it by greatly reducing the likelihood of hazard realization.

Redundant Design for Risk Reduction

In many technology applications, the principle of “redundancy” guides efforts to reduce the realization of predicted hazards. Redundant design for reducing risks posed by escapes from aquaculture operations involves applying a mix of different types of confinement measures, where each type has a fundamentally different vulnerability to failure (for example, as recommended by Brister and Kapuscinski 2002; Kapuscinski and Brister 2001; and the Scientists’ Working Group on Biosafety 1998). By mixing confinement measures with different vulnerabilities, one increases the chances that failure of one barrier will not breach all the barriers to escape of organisms from the aquaculture operation. Physical barriers induce 100 per cent mortality through such physical alterations as imposing lethal water temperatures or pH to water flowing out of fish tanks or ponds before the effluent is discharged to the environment. Mechanical barriers are devices, such as screens, that hold back any life stage of the organism from leaving the aquaculture facility. Biological barriers, such as induced triploidy that makes

adults of some fish species functionally sterile, are those that prevent any possibility of the organism reproducing or surviving in the natural environment.

Two possible approaches to risk mitigation for escapees from aquaculture are localization and use of local fish as broodstock (Hindar et al. 1991). Localization is the confinement of aquaculture operations to designated areas so that the geographic range of impacts is reduced. Use of local broodstocks minimizes genetic differences between escaping and natural fish, which reduces the likelihood of harmful fitness effects from interbreeding. Risk still exists because of genetic changes due to domestication during hatchery rearing, but this option will prevent the introduction of highly alien genes, and pathogens, into the natural populations.

Risk Tracking (Monitoring)

Monitoring aquaculture operations to detect escapees and their impacts can serve two roles. Firstly, monitoring can determine if the risk reduction measures were adequate; when risk reduction measures prove to be worse than planned for, this information can guide responsible parties to develop and implement corrective action; and, finally, determine if corrective action adequately resolves the concern(s). Table 1 focuses on this first role of monitoring. Secondly, monitoring can aim to learn more about a given species or cultured stock's likelihood of imposing or not imposing adverse consequences. It provides important new knowledge that can then improve future risk analysis of other aquaculture operations. The desired role of monitoring will drive decisions regarding the types and duration of steps taken.

Reference Points

While planning for risk monitoring, it is important to establish reference points that trigger corrective actions (Caddy and Mahon 1995). For aquaculture, reference points should address conditions of escape (such as number of escape events, number of escapees), gene flow (for example presence of hybrid offspring), and population and community dynamics (for example, percentage of declines in species abundance or diversity). For example, monitoring could determine if the numbers of fish escaping from a given aquaculture facility has remained below, at, or above the level

chosen as a risk reduction measure. If monitoring detects numbers of escapees above the desired level, then decision makers would implement corrective actions. Generally, corrective actions could attempt to remove escaped organisms from the natural environment, limit their movements in order to halt wider dispersal of escapees, and alter operations to minimize chances of future escape or to reduce the likelihood of adverse consequences from escapees. Biosafety planning should identify corrective actions and personnel responsible for implementing the actions for each reference point established.

Importance of Baselines

Key to any monitoring of impacts on natural populations is baseline information about the natural communities possibly affected by an aquaculture operation. This begins with knowledge of the species present and, preferably, some idea of their abundance. Knowledge of the species present is necessary to monitor for extirpations (i.e., a potential adverse consequence) and, if there are closely related species present, for undesired hybridization between one or more of them and escapees from aquaculture operations. Abundance estimates - at least rough measures such as catch per unit effort in an experimental netting, relative abundance in fishery catches or experimental sampling - are also needed to provide a baseline for monitoring changes in the fish community structure when the changes are less drastic than complete extirpations.

Baseline genetic profiles are necessary to monitor gene flow. In cases of hybridization, species-specific genetic markers must be identified. For example, protein, mtDNA, and nuclear DNA species-specific markers are available for many tilapia species (Penman and McAndrew 2000). In cases of interbreeding within a species, genetic differences between cultured and natural populations must be identified and quantified. Natural populations throughout a species range should be sampled to reveal the existing population genetic structure (between-population genetic variation) within species. Specific DNA markers for genetically modified organisms can easily be developed from unique sequences within the inserted DNA construct (from the protein-encoding gene or promoter sequences). Baseline profiles with several genetic marker types are preferable, because the cost and ease of application and the level of resolution will

differ between types (for example microsatellite DNA markers typically reveal more variation and higher resolution than proteins, but cost more). DNA markers amenable to polymerase chain reaction (PCR) amplification can be applied with minimal amounts of tissue, including air-dried fish scales or fin samples. If resources are not immediately available for genetic analyses, samples such as these could be archived (Rivers and Ardren 1998) for future analysis as the need arises (for example a new aquaculture facility or species is proposed).

Conclusion

A comprehensive aquaculture biosafety program must incorporate assessment and management of risks associated with escapes of aquatic organisms. The realization of a hazard (i.e., an escape event) can initiate a cascade of consequences that may harm biodiversity and other ecological resources, and ultimately the social and economic welfare of affected parties. Proposed and ongoing aquaculture operations should be assessed in terms of the likelihood that a hazard and its consequences will occur, and the severity of the consequences. The identification of hazards those are likely to be realized or have severe consequences signals the need for risk reduction measures and a monitoring program to determine if such measures are adequate. Aquaculture programs operated with a commitment to biosafety during planning and operations offer the promise of food, jobs, and income, while maintaining biodiversity and ecological integrity in the surrounding natural environment.

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