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Non-Native Species in Aquaculture: Terminology, Potential Impacts, and the Invasion Process

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Zebra mussels clog water pipes of power plants in the Great Lakes region. Boaters on the Mississippi River are injured by jumping carp. Predatory and scary-looking snakeheads prowl the Potomac River. These are just a few examples of an issue that has become a global problem. Hundreds of aquatic species have been moved outside their native ranges by humans. Some species are moved incidentally as hitchhikers, as in ballast water or on boat trailers. However, many economically important activities such as aquaculture, the aquarium and water garden trade, the live seafood trade, and commercial and recreational fishing can serve as pathways for the introduction of non-native aquatic species. Many non-native species of crops, livestock and sport fish are economically beneficial and socially important. Unfortunately, some introduced species become pests and may cause economic losses, prey on and compete with native species, alter aquatic habitats, and invade parks and preserves.

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The problem of non-native species has attracted increasing attention from the media, governmental agencies, and non-governmental organizations. In the United States, substantial amounts of public resources have been committed to eradication and control programs. For example, about $10 million to $15 million are spent annually controlling sea lamprey (*Petromyzon marinus*) in the Great Lakes. There is a growing bureaucracy of agencies and interagency groups (e.g., National Invasive Species Council, Aquatic Nuisance Species Task Force) that have coordination, management or regulatory responsibilities relative to non-native aquatic species. There are frequent media stories highlighting the dangers of Asian carp, snakeheads, zebra mussels and other high-profile non-native species. In addition, some environmental advocacy groups have adopted invasive species as a "hot button" issue.

This environmental issue has important implications for aquaculture and associated activities. Aquaculture is frequently criticized as being a major introduction pathway for non-native species. This industry is vulnerable because so many cultured finfish and shellfish species are non-native. For example, non-native goldfish, grass carp, koi, sturgeon, tilapia, tropical fish, trout, ornamental snails, prawns and shrimp are produced in the southeastern U.S. Culture systems such as ponds are viewed as likely sources for species introduction. Some critics argue that maintaining non-native species in any culture system, including indoor, recirculating systems, will eventually lead to their introduction into the wild. Aquaculture may also contribute to the spread of non-native species when organisms such as snails, pathogens or unwanted fish hitchhike during transport. All of these vulnerabilities and perceptions are increasing the regulation of aquaculture, including prohibitions on culture species and restrictions on culture methods.

Terminology

Definitions are critical to communication within any scientific field. The misuse of and confusion over definitions used with non-native species hinders scientific study and hampers the management of problem species. Some of this confusion stems from a lack of standardization of various synonymous words. For example, "non-native," "nonindigenous," "introduced," "alien," and several other words are generally synonymous, although there may be subtle differences in interpretation. All these terms describe a species moved by humans outside of its native range.

Of course, the range of any species can change naturally so there must be some objective determination of what the "original" native range of a species is. For North and South America, a species is native if it was present in its current range before the arrival of Christopher Columbus in 1492.

Words such as "exotic" and "foreign," used to describe species from another country, and "transplant" or "native transplant," used to indicate species moved within a country, are specific subsets of the broader terms.

A few terms are controversial because they also have common, non-scientific meanings. For example, the word "exotic" can be used very broadly to mean any non-native species; but it should not be used in this context because it can also have a positive connotation, as in an exotic

Common Definitions in Invasion Ecology

- **Non-native, nonindigenous, introduced, alien**—Broad and interchangeable terms for a species moved by humans outside of its native range.
  - **Exotic:** A species from another country.
  - **Transplant:** A species moved within a country.
- **Cryptogenic species**—A term used to indicate a species of unknown native status. The species may be native or it may have been introduced before adequate surveys were conducted or introduction records kept.
- **Feral species**—A cultured species that has escaped and has established populations outside of culture.
- **Introduction**—Human-mediated movement of an organism into a previously unoccupied geographic area. Some use this term to include cultured species, but this term is best reserved for species outside of human control.
- **Invade, colonize**—Ecological terms used to describe movement or entry of a species into a new area. These terms should not be confused with the term "invasive species" because they do not imply negative effects. Invasion and colonization are the terms used to describe the process.
- **Invasive species**—A nonindigenous species that causes (or has a high probability of causing) ecological or economic harm or harm to human health.
- **Native species**—A species occurring within its natural range. Because natural ranges change over time with changing environmental conditions, a reference time is often included. For North America, a species is native if it was present before the arrival of Christopher Columbus in 1492.
- **Natural range extension**—Term used to describe expansion of a species range without the direct action of humans. Species ranges frequently contract or expand because of a variety of environmental and demographic influences.
- **Naturalized species**—An established, non-native species that integrates into the native community to the extent that it is often assumed to be native. Mostly used to describe plants.

Definitions of Population Status

- **Established species**—A non-native species population that is persistent, reproducing and self-sustaining; has spread beyond a localized area; and is likely not vulnerable to eradication by human action or natural events.
- **Formerly reproducing**—A non-native species population that was reproducing at one time but has subsequently disappeared due to intentional eradication by humans or extirpation due to natural processes.
- **Locally established**—A persistent, self-sustaining, reproducing population that is present only in a localized area and is likely vulnerable to eradication by human action.
- **Reported**—A non-native species collected without evidence of reproduction.
- **Reproducing**—A non-native species where there is evidence of reproduction but the species is not yet successfully established. Some include locally established species in this grouping.
- **Source-sink dynamics**—Where one population (the sink) relies on immigration from another population (the source) for its persistence. Sink populations may be confused with established or locally established populations but will disappear if the influx of new individuals from the source population is eliminated.

vacation destination. Much of the confusion about definitions and the misuse of terminology stems from the overuse of value-laden, subjective words such as "invasive" and "nuisance." These terms often are misused to denote any non-native species, but properly mean that the species in question does ecological or economic harm or poses a threat to human health. Harm can be a subjective concept and few species have well-documented negative effects. In reality, only a small subset of all introduced species can be accurately labeled as invasive; however, some of these are damaging pests.

Introductions from aquaculture

A number of species have been introduced from aquaculture, including carps, ornamental fishes, salmonids and tilapias. Cultured organisms may escape either from production facilities, during transport, or from end-users. Or, non-native aquacultural species may be deliberately released. Examples are unwanted ornamental fish released by aquarium hobbyists or leftover bait released by anglers.

According to the U.S. Geological Survey (USGS), 91 fish species have been introduced into the U.S. through aquaculture (*http://nas.er.usgs.gov/*; September 2007). More than half of these species are ornamental, although some also have other uses such as bait or food. Most introduced species are not established, and some that are have limited introduced ranges. However, a few species are widely cited as damaging, at least in some locations (e.g., carps, trout and tilapia, although most of these have been introduced from a variety of sources besides aquaculture). It should be noted that 91 is an overstatement of the number of species introduced from aquaculture based on the information presented in the species accounts. It is often difficult for scientists to determine exactly how a species was introduced and in many cases more than one plausible pathway, including aquaculture, was discussed in the species accounts.

Critics often confuse the federal, tribal, state and private hatchery system that produces non-native fish for stock enhancement with the commercial aquaculture segment where the live product is usually not intended for release into open waters. The propagation of fish for intentional stocking has been responsible for the release of many more species than commercial aquaculture. For example, 351 species of freshwater fish in the USGS database were intentionally stocked as sport fish, food fish, forage species, mosquito control or for other purposes. This is not a criticism of intentional stocking programs, but it does illustrate the relative importance of various pathways.

Potential negative effects

When non-native species are used in aquaculture, a particular concern is the possibility that they might have negative effects if they escaped or were released into the environment. These negative effects include competition, predation, habitat alteration, reproductive inhibition, genetic alteration, or pathogen introduction.

Competition occurs when two or more species share a resource, their use depletes the resource, and resource depletion limits their populations. Competition for food, spawning sites or space is most common. Food competition is difficult to detect but is often assumed to occur if species have similar diets. For example, both native paddlefish (*Polyodon spathula*) and bighead carp (*Hypophthalmichthys nobilis*) consume zooplankton. Some experiments suggest that these two species compete, but it is difficult to be certain because zooplankton is abundant, its production rate is high, and it is unknown whether these two fish species actually eat enough zooplankton to limit their own populations. Tilapia may aggressively compete with native sunfish for nesting sites, perhaps reducing sunfish recruitment in some locations where spawning sites are limited. Competition for space is much more common with plants or with invertebrates that attach to a substrate than with fish. A good example is the green mussel (*Perna viridis*), which can crowd out native oysters and other invertebrates on bridges and other hard substrates.

Predation by non-native species can have an important impact on native species. Although predators may be depicted as "voracious" or "indiscriminate killers" of native species, most introduced predators are functionally similar to native predators and many species do not seem to cause noticeable declines in native species. The most dramatic effect of predators occurs when a novel type of predator is introduced. Novel predators may be larger, more efficient at capturing prey, or have different predatory behavior than native predators. Largemouth bass (*Micropterus salmoides*) introduced into a desert spring in the U.S. Southwest would be novel because this predator is much larger than native fishes in the springs. Another example of a novel predator introduction is the flathead catfish (*Pylodictis olivaris*) that is now established outside its native range in the Florida Panhandle and the Atlantic Coast states from Georgia to New Jersey. Predation from flathead catfish has reduced the abundance of redbreast sunfish (*Lepomis auritus*) and bullhead catfishes (*Ameiurus* spp.) in many river systems. The flathead catfish is so large that it can eat adults of the prey species.

Some species can alter habitat by affecting plants or water clarity. An example of habitat alteration occurs with the introduction of grass carp (*Ctenopharyngodon idella*). This species eats aquatic plants and can dramatically change plant communities, reduce water clarity, and change the composition, abundance and size of fish and invertebrate species. It should be noted that grass carp are often intentionally stocked to control aquatic weeds, many of which may be non-native themselves.

Non-native species may inhibit the reproduction of native species when they compete for spawning sites. Large numbers of non-native fish such as tilapia or carp can also physically disrupt the spawning activities of native fish. In these instances, nesting species such as largemouth bass may not complete spawning, or the male guarding the eggs may be overwhelmed and abandon the nest. This can also occur with high densities of native fish such as catfish or sunfish.

Genetic changes may occur if introduced species successfully spawn with native species. This is a substantial concern with the introduction of closely related species or subspecies, as when rainbow trout (*Oncorhynchus mykiss*) are introduced into waters containing cutthroat trout (*Oncorhynchus clarkii*) or rare subspecies of rainbow trout. Genes from the introduced fish are passed into the genome of the native fish, making it possible for rare stocks to be swamped with new genetic material and thereby go extinct. A major concern for aquaculture is the concept of genetic contamination from escaped or released stocks of cultured native fish. The environments of cultured and wild fish have different characteristics, selection pressures, and rates of survival. Therefore, cultured and wild stocks will differ in the frequency of alleles, alternate forms of the same gene, regardless of the care taken when selecting and spawning broodstock. Escaped or released cultured fish may interbreed with wild fish and may cause shifts in the gene frequencies in the wild stocks. Although there is controversy about what this means from a practical standpoint such as survival, growth or other measures of performance, some scientists and resource managers view the culture of native species as having the same or greater risk as culturing many non-native species.

The introduction of pathogens is another potential threat from the use or introduction of non-native species. Introduced pathogens may reduce the reproduction, growth and survival of wild and cultured stocks. Of particular concern are pathogens that affect economically important or endangered species. One introduced pathogen is viral hemorrhagic septicemia virus (VHSv), which has caused fish kills in the Great Lakes. As a result, regulations now ban the movement of wild and cultured fishes from affected areas and there are a number of monitoring and detection programs that document and limit the spread of VHS. It is unknown how VHSv entered the U.S., but it is thought to have arrived by the natural movement of wild fish or in ship ballast water. Another pathogen is the Asian tapeworm (*Bothriocephalus opsarichthydis*), which infects carps and other minnows, including the federally endangered woundfin (*Plagopterus argentissimus*). It is thought to have reached the U.S. with imported grass carp.

Invasion ecology

Scientists in the field of invasion ecology study species invasions (i.e., colonization) and attempt to develop unifying theories concerning the establishment, spread and effects of these species. Applied aspects of this field include risk analysis. Invasion ecology is a fairly young discipline; its founding is associated with the publication of *The Ecology of Invasions by Animals and Plants* by the British ecologist Charles Elton in 1958. This book is a collection of case histories and anecdotes and lacks the synthesis necessary for maturity within a scientific discipline. Continued reliance on anecdotes and case studies has been a source of criticism of invasion ecology. However, there are signs the field is maturing with the development of unifying theories and better predictive capabilities.

Scientists have become better at predicting whether a particular species may invade and become established. These predictions are based on their knowledge of the biology of the organism (particularly its range of physiological tolerance), the characteristics of the geographic region in question, and the history of introductions of the species into other regions. Nevertheless, the success of predicting the ecological or economic effects of species introduction is mixed. For example, the walking catfish (*Clarias batrachus*) is a problem for some ornamental fish farmers in Florida because it is a predator of small fishes and can reduce production in aquaculture ponds. However, it has not caused the ecological devastation predicted immediately after its introduction in the 1960s. Although the vast majority of non-native species have relatively little environmental impact, there is still uncertainty concerning which species will become problematic. Some characteristics such as a large size (for predators) or a history of problems elsewhere seem to be predictive. However, even small species such as mosquitofish (*Gambusia* spp.) can become pests. The uncertainty about what effect an introduced species may have often continues for decades because of the belief that species that are not a problem today

Definitions Associated with Risk

- **Precautionary principle**—A concept whereby uncertainty regarding consequences leads to a decision to forego an activity, even one with benefits, if the consequences might be serious or irreversible.
- **Risk**—The potential for harm to occur. Risk is a function of the probability of occurrence of an event and the consequences of the event.
- **Risk assessment**—A process for determining the nature, severity and probability of risks.
- **Risk aversion**—The unwillingness to bear or accept risk.

will become a problem in the future. This view is based on observations that there can be lag times (real or perceived) between introduction and species becoming pests. Some argue that predicting the results of species introductions may be nearly impossible because of the complexity of natural systems and the unique qualities of almost all introductions. Nevertheless, risk assessment is based on the assumption that, even if not perfect, reasonably accurate prediction is possible. Risk aversion then leads to the application of the precautionary principle to the use of non-native species in aquaculture. A strictly applied precautionary approach would place severe limits on non-native species and culture systems, and would effectively cripple some segments of aquaculture in the U.S.

Critics have pointed out an apparent bias in the selective application of only a part of ecological theory within invasion ecology. In particular, the field has emphasized equilibrium conditions (i.e., "Balance of Nature") and competitive exclusion between species with needs for similar habitat, food or other resources. In fact, there is a growing understanding in ecology that many biological systems are seldom at equilibrium, and that environmental variability and predation often exert strong influences on communities. Invasion ecology could benefit from increased interaction with other ecological disciplines and should draw more widely from the rich body of ecological theory.

These criticisms point to problems with risk assessments and estimates of the potential effects of non-native aquaculture species. If communities are at equilibrium, then any species introduction is a major disturbance to the system and the risk of culturing any non-native species is high. On the other hand, many introduced species integrate into communities with little apparent effect and, therefore, the risk they pose will depend on their specific characteristics and the habitat and communities of the receiving system.

The invasion process

The invasion process is complex. It depends on the characteristics of the invading species and the invaded system and is highly probabilistic, meaning that there is some probability of success or failure and chance may play an important role. It is difficult for a species to successfully establish and most invasions fail. In fact, a species may be intentionally introduced many times in large numbers into suitable habitat without success. This has occurred frequently with intentional sport fish stocking and with the unintentional introduction of escaped species. Nevertheless, it is obvious that successful invasions do occur.

One simplified way to think about this process is within a probabilistic framework. A species must pass through six steps in sequence to successfully establish in a new location. The outcome at each step has an associated probability of success and each step must be completed before moving to the next step. Therefore, the probability of a species successfully establishing is the conditional probability of the species making it through all the steps.

The first step in the process is introduction. The species must be transported to the new area and it must escape or be released. This is the stage where aquaculturists can be most effective at preventing the establishment of non-native species. The use of native species in aquaculture solves this problem, except for the previously mentioned genetics issues, and can be encouraged. But relying solely on native species is sometimes not practical because of production realities and market demands. In this first step, a non-native species in culture is obviously transported into the region, but the probability of escape depends on the type and operation of the culture system. For example, escape is more likely from net pens located in open waters than from an indoor, re-circulating tank system that releases only small amounts of effluent. The management of facilities also can influence the probability of escape. Compliance with regulations, Best Management Practices (BMPs), and HACCP (Hazard Analysis Critical Control Point) plans helps prevent escape. Examples of good management include screening outlets, controlling elevations on perimeter levees, maintaining the integrity of retention systems, using native predators in retention and detention systems, keeping sites secure, being careful with water pumping, excluding and controlling predators, and following biosecurity protocols. Producers can implement HACCP plans that determine how non-native species might escape from facilities and develop standard operating procedures to address the critical points.

The second step in the invasion process is the survival of introduced individuals. The introduction event itself may be stressful to the organism. Differences in temperature or water chemistry between culture systems and the receiving environment may kill individuals or leave survivors susceptible to predation or disease. Individuals may be physically damaged during escape, as when they pass through a pump or overflow device. Even if newly introduced individuals are not substantially stressed, they are disoriented, often predator-naive, and vulnerable to predatory fish or birds.

In the third step, the introduced species must enter an environment suitable for its long-term survival. The physiological tolerances of the introduced species must match the conditions of the receiving environment across seasons and years. The introduced species can probably survive if the receiving system is similar to its native range. On the other hand, many species do not naturally occur in every habitat or climate where they could possibly live; therefore, species may be ecologically or physiologically matched to other habitats or climates. This means that non-native species may be able to survive conditions outside of the norm for their native range. However, physical conditions, especially temperature for poikilotherms (organisms whose internal temperature varies with the temperature of the environment), may prevent survival. Tilapia and many ornamental fish species are tropical in origin and cannot survive cool winters. The culture of non-native species in regions where escapees cannot survive, such as the inland production of marine species or the culture of tropical species in cooler regions, can prevent establishment but may be cost prohibitive.

If a species is introduced into an environment suitable for long-term survival, the next step is successful reproduction. Reproduction often requires a minimum density of mature individuals. Individuals must be able to locate mates and typically both sexes must be present. However, for some species a single gravid female (e.g., a livebearer such as a mosquitofish) or egg-brooding individual (e.g., mouth-brooding tilapia) could start a population. Environmental conditions must be suitable for reproduction, including all required environmental cues for gonad conditioning and spawning, appropriate substrate for nesting or egg deposition, and necessary hydrologic and chemical conditions for egg and embryo survival. Species adaptable to a wide range of conditions are more likely to reproduce successfully than species with precise spawning requirements. With some species, aquaculturists can reduce the probability that escaped individuals will reproduce by culturing hybrids, monosex stocks or triploids.

Reproduction alone is not enough to categorize a species as established. Successful recruitment of new individuals into the reproducing population requires favorable physical conditions such as temperature or flow and adequate food for larval and juvenile survival. Mortality is often extremely high for larval fishes because of weather fluctuations, predation and starvation. Recruitment is a complex process and variable recruitment, including poor or failed year classes, is common in fishes and many other organisms. If favorable conditions occur only periodically, short-lived introduced species may die off without successful recruitment while long-lived species may be able to persist until conditions are favorable.

The last stage of the invasion process is population expansion or spread. Small populations in limited geographic areas are inherently vulnerable to elimination and chance can play a major role in their survival. For example, chance events such as unusual cold periods or heavy flooding might eliminate a small population but have less effect on a larger population distributed over a wide range containing refuges from the disturbance. Small populations may lack adaptability to the environment because of low genetic variability. Such populations may be doomed if they fall below some minimum threshold number. Moreover, small, localized populations are more prone to simply vanish because of

Probabilistic Framework for the Invasion Process

Escape or introduction event (P1)

↓

Individuals survive introduction (P2)

↓

Introduction into a suitable environment (P3)

↓

Individuals successfully reproduce (P4)

↓

Successful recruitment (P5)

↓

Population expands past easy vulnerability (P6)

The overall probability of successful establishment is the product of the probabilities for each stage of the process (P1 through P6). Because each step is dependent on the preceding one, this is a conditional probability. The overall probability of success is less than the lowest probability in the chain. Even if all stage probabilities are high, the overall probability is far lower. A probability of 0 for any stage gives an overall probability of 0.

$$P_{establishment} = P1 \times P2 \times P3 \times P4 \times P5 \times P6$$

Example 1. A mixture of medium and high probabilities.

$$P_{establishment} = 0.6 \times 0.95 \times 0.95 \times 0.7 \times 0.6 \times 0.6 = 0.136 = 13.6\%$$

Example 2. All high probabilities.

$$P_{establishment} = 0.9 \times 0.9 \times 0.9 \times 0.9 \times 0.9 \times 0.9 = 0.53 = 53\%$$

Example 3. Low probability of escape and five subsequent high probabilities.

$$P_{establishment} = 0.1 \times 0.9 \times 0.9 \times 0.9 \times 0.9 \times 0.9 = 0.059 = 6\%$$

Although this is a basic way to think about the invasion process, actual probabilities are seldom estimated from data and are generally qualitatively termed as low, medium or high. Numerical values were chosen to illustrate representative examples.

unbalanced demographics, where more individuals are dying or leaving the area than are being born or migrating into the area. Relatively small decreases in recruitment or increases in mortality can cause small populations of introduced species to disappear. Nevertheless, some highly successful populations are the result of the introduction of just a few individuals.

It is easier, cheaper, and less disruptive to native species to eradicate introduced species when their populations are small and localized than when they are larger and more widespread. Aquaculturists may have little influence over this stage of the invasion process, but can assist natural resource agencies by quickly reporting escapes of cultured stock or the presence of non-native aquatic species near their facilities so that eradication is a more viable management option.

Summary

Despite many common misperceptions and misrepresentations, the invasive species issue is real and important. The economic costs to governmental organizations in the U.S. and to various industries, including aquaculture, are substantial. Scientific uncertainty and the difficulty of predicting which species will become problematic lead to concerns over the culture and use of non-native species. Although it is difficult for a species to successfully invade and establish a population, many aquatic species have succeeded and a few are damaging pests. Some established species have escaped culture or have been introduced through end-users of live cultured products.

The invasion process can be described as a chain of events, each with a probability of occurrence, and each necessary for successful establishment. Of the six stages, aquaculturists have the most influence on the initial stage, the introduction event, but can also influence subsequent stages (survival through the introduction event, the presence of a suitable environment for long-term survival, and successful reproduction). Compliance with regulations, BMPs and HACCP plans can reduce the probability of an introduction.

This is an important environmental issue for aquaculture that has management, scientific and public relations components. Science-based, objective information about the risks, negative effects, and benefits of non-native species is needed. Private and public aquaculturists, Extension personnel, researchers, natural resource managers, and regulators should make themselves aware of the issues, recognize where there are legitimate concerns, and know how the risks can be effectively and reasonably managed.

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