Chapter 8

Managing Undesired and Invading Fishes

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8.1 INTRODUCTION

Throughout much of history, humans have directly or indirectly facilitated the introduction of fishes and other aquatic organisms into areas where they had not previously existed, places outside their natural geographic distributions. These introductions have dramatically changed biological communities throughout the world. North America is no exception and the continent is now home to multiple species native to other parts of the world. In addition, many aquatic animals native to one or a few drainages and regions in North America have been transported by humans to other drainages and regions within the continent (Fuller et al. 1999). Through time, the many foreign introductions and intra-continental transplants, in conjunction with loss of native (often endemic) species, have resulted in aquatic faunas across North America that are increasingly homogenized and biologically less distinctive.

The motives behind aquatic organism introductions, the means by which they are introduced, and the ultimate outcomes of these introductions are many. A large proportion of introductions have been deliberate, usually a result of authorized stocking by governments or other institutions. However, there have also been a large number of illegal or otherwise unauthorized introductions. In addition, a wide variety of introductions have occurred that are considered accidental or unintended, a by-product of human activities (e.g., construction of a canal that allows dispersal of fish into new areas). In terms of motives, many fishes and certain other aquatic organisms have been introduced to establish food sources, create new fisheries, and restore depleted stocks (Fuller et al. 1999; Wydoski and Wiley 1999). In addition, a diverse array of nonnative and native fishes has been stocked for biological control of unwanted plants, invertebrates, and other fishes, as well as for conservation purposes. Introductions have also occurred as a result of unauthorized liberation of small fishes used as bait (i.e., bucket releases), releases of aquarium and water garden plants and pets, and escapes from aquaculture facilities. Aquatic species have also invaded new environments by way of water craft, usually by attaching to vessel hulls or by being carried in ship ballast water; others have invaded adjacent drainages by way of excavated canals or other artificial water channels (Courtenay 1993; Fuller et al. 1999).

Although introductions do not always result in reproducing populations, introductions have occurred over centuries and have involved large numbers and a wide diversity of organisms. There are now hundreds of nonnative aquatic species with established or permanent populations in North America (Fuller et al. 1999). Depending on a variety of factors (e.g., the type of species or genetic variant), individuals of a nonnative species may—at least over the short term—remain few in number and not disperse far beyond where initially introduced. Often, locally-established populations cause little or no detectable ecological or economic harm (Courtenay 1993). However, a proportion of introduced aquatic organisms become abundant and widespread, and many of these either cause or have great potential to cause substantial ecological and economic damage. These organisms are termed invasive.

The term "invasive species" has been defined a number of ways. In the USA, Executive Order 13112, signed by President Clinton in 1999, defines an invasive species as "an alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health." In the "Executive Summary" of the National Invasive Species Management Plan (NISC 2001), an invasive species is characterized as "a species that is nonnative to the ecosystem under consideration and whose introduction causes or is likely to cause economic or environmental harm or harm to human health." For purposes of this chapter, we use the phrase "nuisance species" to describe invasive, nonnative aquatic species as well as certain native species whose populations have grown to such an extent that they are deemed undesirable.

Because nuisance fishes—whether a nonnative invasive or an undesirable native population—can be very difficult and expensive to eradicate, it is prudent to consider carefully potential unintended consequences prior to introducing nonnative fish deliberately and to look for ways to reduce the likelihood of introductions from by-products of human activities. In some situations, a nuisance aquatic species may be present in one or a few isolated ponds or lakes or other confined water body. In these instances, eradication is sometimes relatively easily achieved. However, in those cases in which eradication is implausible or perhaps too costly, emphasis is placed on developing a management and control program. The ultimate goal of any particular fish eradication or control project depends on multiple factors, such as the type, size, and complexity of the aquatic system, as well as the type, abundance, and geographic distribution of organism or organisms targeted, including their potential for harm. Some methods for management and control have been used for decades whereas other approaches are relatively new or are currently under development. There have also been marked shifts in fisheries management paradigms or basic practices, including acceptance of integrated pest management (IPM) and adaptive management practices. Moreover, it is increasingly recognized that management of nuisance species needs to take into account other environmental stressors, such as global climate change.

In this chapter the history of fish introductions in North America is reviewed and the many different motives and ways in which introductions have occurred and changed through time are described. The challenges faced by natural resource managers, who are forced to remediate complex situations involving multiple vectors of introduction, old and new, and the continual and sometimes unanticipated introduction of new and potentially harmful species are also addressed. Various aspects of prevention, management, and eradication of nuisance fishes, focusing heavily on advances in the field and new ways of thinking about invasive species problems are then discussed.

8.2 HISTORY OF FISH INTRODUCTIONS

Fishes and other aquatic organisms introduced to the inland waters of North America have come from all over the globe (Courtenay 1993, 1995; Fuller et al. 1999). Many of these introduced species have caused little or no observable change in their novel habitats. Some introductions have lead to beneficial uses, such as the numerous valuable recreational and commercial fisheries created throughout the continent. Other introductions, however, have resulted in biotic disruptions, sometimes threatening native habitats and native species resulting in ecological harm and economic costs to society (Fuller et al. 1999). Understanding how and why nonnative nuisance fish were introduced and have become established, as well as how society's perception of introductions has changed through time, helps to inform and enhance current management practices. To highlight the situation and improve understanding, we recognize and describe three distinct periods of fish introductions in North America.

8.2.1 Early Introductions (1800–1950)

Introductions of nonnative fishes into North America began with colonization, population growth, and expansion of European immigrants across the continent. Welcomme (1981) suggested that this period of fish introductions began around the middle to latter part of the 1800s with the development of international trade. However, DeKay (1842) reported the first release of goldfish into the Hudson River, New York, in the late 1600s; thus, the first individuals of this species must have arrived from Europe in the era of sailing ships. The goldfish was the first nonnative fish to become established in the USA and later in Canada and the United Mexican States (Mexico) (Courtenay and Stauffer 1984).

Following the U.S. Civil War (1861–1865), native wild fish stocks were being overexploited and depleted. This led to a growing interest among U.S. government officials, partly influenced by immigrants of European ancestry, to revitalize the commercial fish industry and human food resources by importing and culturing food and sport fishes native to European waters. Many of these fishes were already familiar to immigrants and most of these fishes were already being cultured in Europe. To address this task, the U.S. Fish Commission was created in 1871. The newly formed agency was placed under the direction of the renowned scientist, Spencer F. Baird. Baird immediately arranged for the import of several species of fish from Europe, and, once received, these fishes were cultured and then distributed throughout the USA and its territories (Baird 1893). The transport of live fish into the USA and across the continent was made possible by recent advances in transportation, such as steam-powered ships and transcontinental rail.

One of Baird's early assignments was to send ichthyologist Barton Warren Evermann to Yellowstone National Park to explore its native fish resources and to recommend nonnative fishes to introduce to create sport fisheries in the region (Jordan 1891). Yellowstone National Park, the world's first national park, was established in 1872. Creation of the park signaled the beginning of U.S. conservation efforts, although the push to introduce nonnative fishes into Yellowstone waters was not yet considered to be in conflict with the newly evolved conservation philosophy of the period (Courtenay 1993). In addition, politicians and local governments of many states and U.S. territories also requested fishes of foreign origin for stocking into their waters. In particular, they wanted what was then termed a "wonder fish" from Europe, common carp (Courtenay 1993). Also on the wish list was Loch Leven or German trout, which we know as brown trout, and stocks of this fish were imported from both Scotland and Germany and initially cultured in Michigan (Laycock 1966). Largely because of those early introductions, both common carp and brown trout became established in the wild and remain widely distributed throughout most of the USA (Fuller et al. 1999).

Two other fishes from Europe, ide and tench, were also imported by the U.S. Fish Commission. These species along with goldfish and common carp were being cultured and displayed by the commission in ponds near the banks of the Potomac River in Washington, D.C., when a flood in 1889 reached the ponds and most of the fish escaped into the river (Baird 1893). It is believed that the escaped fishes persisted in the Potomac River for a time but eventually disappeared and are not part of the fauna now (Courtenay 1993; Jenkins and Burkhead 1994). However, ide and tench were subsequently introduced into other U.S. waters and reproducing populations exist, but these remain localized (Fuller et al. 1999).

Beginning in the late 1800s (and continuing until the late 1940s), fertilized eggs, fry, and juveniles of fishes of European origin (and eastern U.S. native fishes including brook trout, American shad, and striped bass) were moved from hatcheries into containers for transport behind railroad steam engines hauling specially designed “fish cars.” These rail cars were equipped with cooling (initially with ice) and aeration (initially by hand); the methods improved over time because of innovations in cooling and aeration technologies (Leonard 1979). Transport of fishes from the eastern to western USA by rail began in 1873 with the intent of establishing new fish populations in targeted novel waters. On return trips from the western USA, fish cars carried western native fishes such as rainbow trout for introduction into midwestern and eastern waters. By 1923, over 72 billion fish had been moved by railroad fish cars. The last such rail fish car was retired in 1947 (Leonard 1979).

In addition to planned and deliberate fish introductions, transport of fishes by rail car also resulted in a number of unauthorized fish introductions. For example, in 1873 a bridge collapsed and the train’s fish cars, carrying some 300,000 live fish (mostly American eels and American shad and some yellow perch), plunged into the Elkhorn River near Omaha, Nebraska, releasing their live cargo into the wild (Fuller et al. 1999). Information in early U.S. Fish Commission reports also indicates that, on occasion, fish cars were “parked” on or near a bridge over a river, and train personnel released a portion of their containers of live fish into the rivers below. Some of these releases were authorized, but it is presumed that others were not. Unfortunately, few official records of these releases exist except in notes of personnel traveling in the fish cars, so information on localities, dates, or species released is not available or is hidden within the massive U.S. Fish Commission reports.

8.2.2 Second Period of Introductions (1950 to cerca 1975)

Except for a few foreign commercial fishes, mostly of European origin, very few nonnative fishes of foreign origin were introduced to North American waters during the early decades of the 1900s (Courtenay et al. 1984, 1986; Fuller et al. 1999). However, after World War II (post-1945) and the advent of intercontinental jet cargo aircraft in the early 1950s, live fish could be rapidly transported from one continent to another, often in a few hours. Ornamental fish importers pioneered the use of plastic bags for carrying and shipping live fishes by air and land. The plastic bags are sometimes injected with pure oxygen to ensure fish survival and further protected by placement in Styrofoam™ containers. This traffic increased dramatically, with most imported fishes and plants destined for the aquarium fish industry and hobbyists. Other species were later imported similarly for potential use as biological control organisms and in aquaculture. This practice continued and Ramsey (1985) estimated that over 100 million fish were imported by air annually during the early 1980s.

During this same period, the number of facilities designed for culturing fishes to supply a growing aquarium fish trade and hobby in North America increased, especially in subtropical areas of Florida. Boozer (1973) estimated that 80% of all aquarium fishes sold in North America were being cultured in Florida. Based on estimates of imports by Ramsey (1985), 20% of aquarium fish imports were fishes not cultured in North America at that time.

There have been escapes of fishes from a number of culture facilities into open waters (Courtenay and Stauffer 1990; Courtenay and Williams 1992). In addition, as the aquarium fish hobby grew, the number of species released by hobbyists into North American waters increased (Fuller et al. 1999); additional species and introductions continue to be observed in open waters from this vector. In warmer waters such as those in southern Florida, Texas, and California, in Hawaii, and in thermal spring outflows in the American West (as far north as Montana and Alberta), a variety of released aquarium fishes have become established as reproducing populations. Admittedly, it is not always possible to ascertain the true source of introduced populations—whether a pet release or escape from a culture facility. Regardless of origin and motive of introduction, some of these introductions have had dire consequences to native fishes, particularly those with populations endemic to the American Southwest and northern Mexico (Courtenay et al. 1985; Deacon and Minckley 1991; Jelks et al. 2008).

During this period, nonnative fishes also were commonly introduced because of their potential as biological control agents. A wide variety of small and large fishes were involved in this endeavor, and, depending on species, their intended uses included control of rooted aquatic plants, algae, and mosquitoes (even though most fishes are opportunistic feeders) (Courtenay and Meffe 1989; Courtenay 1993; Fuller et al. 1999). Some managers, focused on the beneficial uses of these species and perhaps under the impression that correcting unintended consequences of using nonnative fishes for biological control would be relatively easy, gave little attention to assessing the potential risks associated with these introductions.

Some introductions of fishes as biological control agents resulted in achievement of management goals. Stocking the Asian cyprinid grass carp has led to control of macrophytes in many waters across the USA (Cassani 1996); stocking Pacific salmonids in the Great Lakes led to declines in invasive alewives (Madenjian et al. 2002); and stocking striped bass has resulted in reductions of native nuisance threadfin and gizzard shad populations in various reservoirs around the country (Axon and Whitehurst 1985). There are nuances to each of these successes, however: population size of grass carp is important to success—overstocking or subsequent reproduction can lead to loss of all submerged vegetation to the detriment of desired species (Hanlon et al. 2000); reliance on alewives as prey can lead to thiamine deficiency in native lake trout as well as in introduced Pacific salmonids, resulting in early mortality syndrome in their progeny (Honeyfield et al. 2005); and the circumstances under which control of shad species can be achieved depends on the size structuring of the prey base (Dettmers et al. 1998).

Stocking of grass carp deserves special attention due to the numerous success stories of its effective control of aquatic vegetation, its continued use, its widespread availability, and the unintended consequences of using grass carp for biological control. Grass carp was identified in the 1960s as a potential biological control for nuisance aquatic macrophytes owing to its preference for consuming such vegetation (Courtenay 1993). However, those promoting introduction and use of grass carp for plant control assumed that this Asian species was so specific in its reproductive habits and habitat requirements that it could not establish reproductive populations in North American waters (Courtenay 1993). However, not all agreed with this assessment. For instance, Lachner et al. (1970) expressed concern that natural reproduction of grass carp in North American waters was probable. Their fear was proven correct by Conner et al. (1980), who confirmed that grass carp were reproducing in the wild in the Mississippi River basin as early as about 1975. Since that time grass carp has become widespread and it is now presumed established in 18 states in the USA (Nico et al. 2010). An additional concern associated with grass carp is that it carries a nonnative parasite, the Asian carp tapeworm, which spread to baitfishes in polyculture with grass carp. Infected baitfishes, cultured in midwestern states and sold in western states, passed this parasite to endangered native fishes (Kolar et al. 2007). Additional species of Asian carps (black carp, bighead carp, and silver carp) introduced in the USA after grass carp are also known to be carriers of this particular parasite, as well as other parasitic species.

Although wild populations of grass carp spread and reproduce, there remained a strong desire for continued use of the species for control of nuisance aquatic plants. To reduce the risk of additional reproducing populations and widespread establishment, substantial effort was invested in the research and development of sterile or nonreproductive grass carp. In 1985 an apparently reliable technique, one using pressure to shock fertilized eggs, was found to produce near 100% triploid (sterile) fry (Cassani and Caton 1985). This new and relatively inexpensive technology expanded interest in grass carp for biological control, but uncertainty regarding ploidy of fry lingered. However, shortly thereafter an economical method for determining ploidy of grass carp fry by means of a Coulter counter was made available (Wattendorf 1986). The U.S. Fish and Wildlife Service (USFWS) developed a standard operating procedure using Wattendorf's method to validate that shipments of grass carp were 100% triploid (Mitchell and Kelly 2006) and began offering this service to states. States responded very favorably to the program, with over 30 states participating through time (Mitchell and Kelly 2006).

8.2.3 Third Era of Introductions (Post-1975 and Continuing)

Recently, three additional species of Asian carps have been imported into North America, and all three have escaped or been released into inland waters. Two species, the bighead carp and silver carp, are well established, very abundant, and alarmingly invasive. Rationales for importation of these two species were biological control of nuisance phytoplankton in sewage treatment ponds, enhancement of water quality in aquaculture ponds, and potential as food fishes (Kolar et al. 2007). Because these carps feed primarily on plankton, the base of the food chain for all larval and some juvenile and adult native fishes, there is concern that they could have major negative effects on native fish populations. A third species, the black carp, used by the aquaculture industry to control snails in culture ponds, is possibly established in the lower Mississippi River basin (Nico et al. 2005). Because black carp feed almost exclusively on mollusks and many native freshwater mussels are in decline and are imperiled, there is concern that black carp will further threaten their survival.

The aquaculture industry in North America experienced rapid growth during the 1960s and 1970s (Courtenay and Stauffer 1990). To lower production costs and provide convenient access to water, culture facilities were initially often sited in lowland areas, typically near canals or flowing waters, thereby increasing the risk that any escaped individuals could find suitable waters to colonize downstream of the fish farm. Many states have since enacted more stringent legislation and regulations pertaining to the construction of aquaculture ponds and location of aquaculture facilities. Escape from aquaculture facilities (of all types—baitfishes, food fishes, and aquarium species) has been reported as a means of introduction into the wild for over 90 fish species in the USA (http://nas.er.usgs.gov). For some of these species, aquaculture was only one of several vectors by which the species was introduced (e.g., common carp, goldfish, Asian carps, and mosquitofishes). For others, however, releases from culture facilities are almost certainly the primary vector of introduction (e.g., a nonnative species found downstream of a fish farm producing that species). This phenomenon spawned a series of articles in a leading aquarium hobbyist magazine documenting the numerous locations in Florida where nonnative tropical fishes can be easily collected "without leaving the country" (Ganley and Bock 1998).

Escapes from the aquarium fish culture industry, in addition to releases by aquarium hobbyists, have resulted in the introductions and establishment of suckermouth armored catfishes of the genus *Pterygoplichthys*, commonly known as sailfin catfishes, in the USA and Mexico (CEC 2009). In aquaria, these sailfin catfishes are used to control algae. However, members of this genus are large fish that grow rapidly, often becoming too large for their aquaria. Release of adult sailfin catfishes by aquarists is presumed to be the main reason why these fishes have become established in many streams and lakes in Florida, Hawaii, Texas, and Mexico (Nico and Martin 2001; Wakida-Kusunoki et al. 2007; Nico et al. 2009). Once established, sailfin catfishes excavate large burrows in the banks of lakes and streams. These burrows are used as spawning and nesting sites and also contribute to bank erosion (Nico et al. 2009). In some waters of Mexico, such as Infiernillo Reservoir, sailfin catfishes have become dominant, replacing native species and even some nonnative tilapias that used to dominate economically-important fisheries there and causing collapse of local commercial fisheries (Mendoza et al. 2007).

Stocking of fishes by state and provincial agencies to enhance angling opportunities, a practice that began with the U.S. Fish Commission in the late 1800s, has remained an important vector by which nonnative fishes are introduced into North American waters (Courtenay 1993, 1995; Fuller et al. 1999). In the USA these introductions have been aided by annual federal funding. Anglers have been typically pleased with the results of stocking, and a large number of economically-valuable fisheries rely on stocking. However, this practice is controversial because of irreversible changes to systems' natural ecology and aquatic biota. Nonnative foreign and transplanted fishes used in stocking are typically cultured in federal, state, or provincial hatcheries. In some regions, the arguments against stocking center on documented problems created by the culture and release of various salmonids popular for sportfishing. Rainbow trout, native to waters west of the Continental Divide, has been widely introduced. In western states it has hybridized with some native trout to their detriment (Fausch 2008). Brook trout, introduced to western U.S. waters from its native distribution in eastern North America has displaced cutthroat trout from portions of its native distribution. Ironically, introduced rainbow trout has displaced brook trout in portions of its native distribution (Fausch 2008). Brown trout, introduced to the northeastern USA and eastern Canada in the late 1800s to early 1900s, has hybridized with native Atlantic salmon to the detriment of the native species (McGowan and Davidson 1992).

Transoceanic shipping has been the vector of introduction for many nonnative aquatic species to both coasts of North America and the Laurentian Great Lakes, particularly in recent decades. Although there are other vectors by which ships can release organisms (e.g., from hull fouling), clearly the most important in recent decades has been the emptying of ballast tanks while cargo is being loaded. Filling ballast tanks at one port for release at another is necessary to ensure stability of the ship during overseas voyages if the ship is not loaded with cargo. However, the water from foreign ports contains aquatic species, usually invertebrates but sometimes small fishes. Since the completion of the St. Lawrence Seaway in 1959, at least 28 nonnative species have become established in the Great Lakes from ballast water releases (Grigorovich et al. 2003). Some of these species have become invasive, most notably zebra and quagga mussels. Since their initial introduction in the 1980s, these mussels have spread throughout the Great Lakes, down the Mississippi River, and throughout parts of that basin; since 2007 quagga mussels have also been spreading in waterways of the western USA, including lakes Mead, Mohave, and Havasu (Benson et al. 2010). Both mussel species have had a history of clogging intake pipes to power plants, dam operating structures, and boat engines. Controlling invasive mussels cost electric power generating facilities on the Great Lakes alone an estimated US$10–30 million annually between 1989 and 2004 (Connelly et al. 2007). Since their initial introduction, spread of zebra and quagga mussels has been facilitated unintentionally by activities of recreational boaters (in live wells, bilge water, or on the hulls of boats).

The introduction of invasive mussels into the Great Lakes may have "paved the way" for the successful establishment of other species also introduced by ballast water from the Ponto-Caspian region, particularly the round goby, a fish whose diet includes zebra mussels in its native distribution. Both round goby and tubenose goby were first discovered in the St. Clair River, Michigan, in 1990 (Crossman 1991; Jude et al. 1995). The round goby, in particular, has since become widely distributed throughout the Great Lakes. During the 1980s, another European fish, the ruffe, entered North America via ballast water and became established in the Great Lakes region (Ricciardi and Rasmussen 1998).

Akin to the situation in the Great Lakes, California currently has four species of introduced gobies from the western Pacific, whose introduction originated from ballast water released from transoceanic ships that entered California harbors. Two of the gobies venture into and can become established in inland waters. One of these, the shimofuri goby, an aggressive species with high reproductive potential, has become invasive in freshwater areas. Discovered in California waters in 1985, its introduction was undoubtedly via ship ballast water and its invasion partly explained by the presence of some of its preferred foods, Asian invertebrates that also arrived through ballast water release (Moyle 2002).

Another vector by which nonnative fishes have been introduced into North America has been as human food, beginning with introductions of European fishes by European immigrants and, more recently, introductions of Asian fishes by Asian immigrants. There is a wide tradition in many Asian cultures of providing live fish at food markets. The purchase and occasional release of live fish from the live food fish industry in North America is an increasingly common vector of introduction. Among fishes imported to satisfy this trade were snakeheads. Snakeheads are top predators, mostly native to subtropical and tropical regions of Asia and Africa; thus, parts of North America with similar climates have a higher risk for establishment of these species. The northern snakehead is an exception to this rule and can survive in waters that freeze (Courtenay and Williams 2004).

Courtenay and Williams (2004) reported introductions of other snakehead species and reviewed the history of establishment of the northern snakehead and its subsequent eradication from a pond in Maryland. After the eradication, additional established populations of this cold-tolerant snakehead were found in the Potomac River of Maryland and Virginia and later in Arkansas, Pennsylvania, and New York. Other species of snakehead, also probably introduced via the live fish food markets, are also present. For example, in 2000, the bullseye snakehead was found established in southeastern Florida, the first record of this species in North American waters (Shafland et al. 2008).

8.3 PREVENTION OF UNINTENDED INTRODUCTIONS AND REDUCTION OF RISKS OF DELIBERATE INTRODUCTIONS

In part because of a lag time between introduction, detection, and identification by management agencies of introduced species, managing nuisance fish populations often begins only after the species has already become established and achieved nuisance levels. Management options at this point in the invasion sequence are generally fewer and more difficult than if the species had been detected earlier, when less abundant and widespread (Figure 8.1). Not

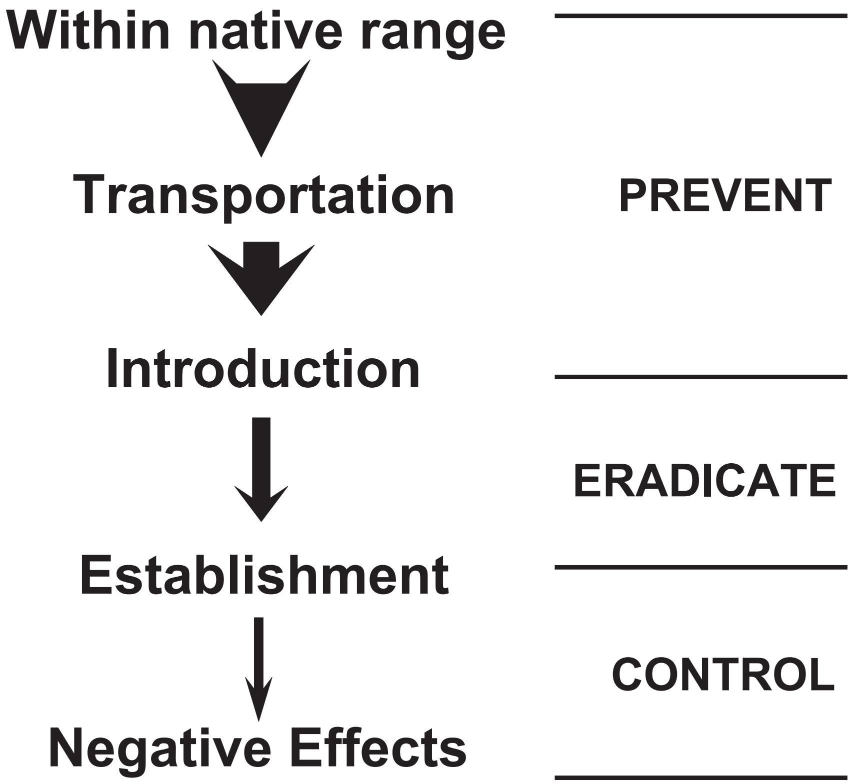

Figure 8.1. In order to persist in a novel ecosystem, nonnative species must survive a series of transitions that occur in a predictable sequence. Individuals must survive transportation from their native ecosystem and introduction into the novel ecosystem in sufficient numbers; their ecological requirements must be met to an extent that allows reproduction and establishment; at this point, some species go on to become a nuisance, either economically, ecologically, or both (modified from Lodge et al. 2006). Usually, a small percentage of species introduced successfully make these transitions (as indicated by the thinning arrows from one transition to the next). As species become more entrenched in the invaded ecosystem, management options become more limited and move from prevention to eradication or, more often, to control of populations. Control, hopefully below nuisance levels, requires sustained and costly effort.

only are more management options available early in the invasion sequence, but economic analyses have shown that an ounce of prevention can, indeed, be worth a pound of cure when it comes to reducing impacts of invasive species (Keller et al. 2009). For these reasons and because eradicating nuisance fishes is not always a viable option, preventing unintended introductions and taking precautions to lower the risks associated with deliberate introductions is prudent. Therefore, we consider preventing the introduction of nuisance fishes relevant to discussing their management.

In this section we (1) discuss the role of government in the prevention and reduction of nonnative aquatic species; (2) present information on legislation and regulations, best management practices, and education and outreach to prevent unintended introductions of nonnative fishes; and (3) describe measures that fisheries management entities can take to reduce unintended consequences of deliberate introductions (Table 8.1).

8.3.1 Government Agencies and Legislative Authorities

A variety of national and state or provincial agencies and legislative authorities play a role in the management of invasive and other undesirable aquatic organisms across North America. For instance, in the USA issues regarding invasive species are handled by more than 20 federal agencies (U.S. Congress 1993) and a wide variety of state agencies; in Canada, primary responsibility and authority regarding aquatic invasive species rests with two government departments, Fisheries and Oceans Canada (DFO) and Environment Canada; and in Mexico, prevention and control of aquatic invasive species is split between several governmental agencies.

In the USA, the Nonindigenous Aquatic Nuisance Prevention and Control Act of 1990 established an interagency committee to develop and implement a program to prevent the introduction and dispersal of aquatic nuisance species in U.S. waters; to monitor, control, and research these species; and to disseminate information. Two regional panels were created to identify priorities, coordinate nonnative species program activities, and advise public and private interests on control efforts. These and additional regional panels have proven useful and effective in coordinating issues regarding aquatic invasive species (e.g., developing national management plans for invasive species of particular concern, disseminating information of regional scope, and developing rapid response plans).

Federal efforts in the USA dealing with invasive species are coordinated by the National Invasive Species Council (NISC), an interagency group established in 1999. In 2001, NISC released its first National Invasive Species Management Plan, which it revised in 2008 (NISC 2008). The 2008 plan calls for federal agencies to use relevant programs and authorities to prevent introductions of invasive species; find and eliminate or reduce new invasive species through early detection and rapid response; stop their spread and minimize impacts through control and management; restore native species and habitats; rehabilitate high-value ecosystems and processes; and maximize effectiveness on invasive species issues through organizational collaboration. However, most fisheries management of inland waters in the USA falls to state agencies. At least 39 states currently have invasive species councils or committees (R. Westbrooks, U.S. Geological Survey, personal communication). These groups are typically composed of people with diverse backgrounds but share an interest in the control and management of invasive species within the state; their goal is to facilitate prevention and control efforts. Some groups deal exclusively with invasive plants, whereas others are inclusive of aquatic species.

Table 8.1. Common vectors by which nuisance fishes are introduced into inland waters and methods used to minimize their associated risks (in the case of authorized stocking by governmental agencies) or to minimize introduction events (remaining vectors). Capitalized jurisdiction represents the more common level of regulation.

	Prevention measures		
Vector of introduction	Regulation	Best management practices	Education and outreach
Ballast water	FEDERAL, state	X	
Aquaculture industry	Federal, STATE	X	
Live food fish industry	Federal, STATE	X	X
Stocking by government agencies	Federal, STATE	X	X
Water garden and aquarium pets	Federal, STATE		X
Unauthorized stocking	Federal, STATE		X
Bait bucket releases	State		X
Recreational activities	State	X	X
Research activities	State	X	X
Diffusion from neighboring waters			X

Both Canada and Mexico responded to the adoption of the 1992 United Nations Convention on Biodiversity by producing national biodiversity strategies (Minister of Supply and Services Canada 1995; CONABIO 2000; Muñoz et al. 2009). Each of these strategies recognizes invasive species as a threat to national biodiversity, and both countries followed these national biodiversity strategies with developing national plans addressing the prevention and control of invasive species (CCFAM 2004; SMARN 2009; Muñoz et al. 2009).

Because aquatic and other invasive species are introduced through specific human-mediated vectors, Canada addresses vectors separately to reduce the threat. For example, a set of guidelines addresses authorized introductions, including aquaculture and fish stocking (DFO 2003); ballast water is regulated by the Canada Shipping Act; and other aquatic vectors of introduction are addressed by the national plan addressing aquatic invasive species threats (CCFAM 2004). In effort to help control, eradicate, and prevent introductions that threaten ecosystems, the DFO formed the Centre of Expertise for Aquatic Risk Assessment (CEARA). This center has developed scientifically defensible risk assessment standards and tools to identify key points in the invasion pathway and maximize efficient use of limited resources to the greatest effect.

In Mexico, prevention and control of pest species, especially those associated with agriculture and aquaculture, are under the purview of the federal agency Servicio Nacional de Sanidad, Inocuidad y Calidad Agroalimentaria (SENASICA) (Muñoz et al. 2009). Although a draft national plan on invasive species has been prepared (SMARN 2009), and Mexico is party to several international cooperatives addressing invasive species issues, the country does not yet have a national policy addressing invasive species in natural areas (Muñoz et al. 2009). Authorities and mandates regarding prevention and control of aquatic invasive species are split among governmental agencies in Mexico. Ballast water is addressed by the Secretariat of Communication and Transports through the Main Directorate of Merchant Marine; the National Secretariat of Environment and Resources, by means of the Office of the Judge

Advocate General, Federal Protection to the Atmosphere and the Main Directorate of Inspection of Wildlife, inspects ports, international airports, and border points; and the National Environmental Policy for the Sustainable Development of the Oceans and Coasts proposes specific strategic targets and tactics to control aquatic invasive species.

In addition to efforts of individual countries, there is an international effort to address the importation of potentially invasive species into North American through the Council for Environmental Cooperation (CEC) via the North American Free Trade Agreement. That cooperation recently resulted in the release of tri-national risk assessment guidelines (CEC 2009).

8.3.2 Prevention of Unintended and Unauthorized Introductions

Consequences of some unintended and unauthorized fish introductions have been costly economically and ecologically (e.g., sea lamprey in the Great Lakes) (Fuller et al. 1999). Because eradication is not always achievable and control efforts are costly, these introductions can have long-term negative effects. Therefore, the most cost effective means of dealing with invasive species is preventing their initial introduction (NISC 2001). Leung et al. (2002), for example, determined that society could benefit by spending up to $324,000 per year to prevent invasion of zebra mussels into a single lake with a power plant (which Leung et al. 2002 pointed out is more than a third of what the USFWS spent in 2001 to manage all aquatic invaders in all U.S. lakes). Below we review the three major avenues that can be pursued to reduce the likelihood of unintended or unauthorized introduction of fishes as the by-products of human activities.

8.3.2.1 Legislation and Regulation

One method of preventing introductions of nonnative aquatic species is to regulate their initial importation and to define or regulate what is allowable with regard to the species after importation. In general, comprehensive legislation addressing potentially invasive plants and animals is lacking in the USA, Canada, and Mexico. In each country, a patchwork of federal and, in some countries, state or provincial, agencies oversee the different facets of the import process while often focusing on only particular types of plants or animals.

Most relevant to the importation of potentially invasive fishes in the USA are duties falling to the USFWS (Stanley et al. 1991),which may prohibit importation and interstate transport of injurious terrestrial and aquatic animals (including mammals, birds, fish, amphibians, reptiles, mollusks, and crustaceans) under the injurious wildlife provisions of the Lacey Act. However, the current list of injurious taxa is short (Table 8.2), the process to list a species as injurious is lengthy, and there are no provisions for emergency listing (Short et al. 2004). The other main federal agency charged with regulating the entry of fishes into the country is the Animal and Plant Health Inspection Service (APHIS) within the Department of Agriculture. The authority of APHIS arises from laws such as the Plant Protection Act and a number of statues collectively referred to as the animal quarantine laws. By means of these laws APHIS can prohibit, inspect, treat, quarantine, or require mitigation measures prior to allowing entry of plant species, their pests, biological control organisms, animals, animal products and by-products, or their host commodities or conveyances (NISC 2001). Currently APHIS has a number of domestic quarantines in place to prevent invasive species from moving within the country (such as the emergency order now in place restricting the movement of certain fishes

Table 8.2. Aquatic animals currently listed under the injurious wildlife provisions of the Lacey Act.

Common name	Scientific name
Salmon[1]	Family Salmonidae
Walking catfish	Family Clariidae
Mitten crabs	Genus *Eriocheir*
Zebra mussels	Genus *Dreissena*
Snakeheads	Genera *Channa* and *Parachanna*
Silver carp (and hybrids)	*Hypophthalmichthys molitrix*
Largescale silver carp (and hybrids)	*Hypophthalmichthys harmandi*
Black carp (and hybrids)	*Mylopharyngodon piceus*

[1] except those accompanied by proper health certification

in the USA to prevent the further spread of the fish pathogen viral hemorrhagic septicemia and special importation restrictions placed on several fishes that are known carriers of spring viremia of carp virus). Lodge et al. (2006) evaluated current U.S. national policies and practices on biological invasions in light of current scientific knowledge and provide a series of recommendations to improve protection from invasive species.

In the USA, states have developed diverse legislation to prevent or regulate the introduction of fishes deemed nuisances (reviewed in Filbey et al. 2002). A variety of actions are variously regulated, including importation, possession, transportation, and introduction. Sometimes paralleling federal regulatory control of aquatic invasive species, state responsibility for prevention and control is often divided, sometimes overlapping, among a variety of state agencies and typically involves departments of natural resources and agriculture as well as a department of environment (Reeves 1999). In some regions, neighboring states regulate the import or introduction of nonnative aquatic species very differently. The state-by-state patchwork of invasive species legislation complicates and can frequently hinder effective prevention and management (Nico et al. 2005; Kolar et al. 2007). In some cases, different states located in the same river basin may clash, for example, with one promoting introduction of a commercial fish while that species may be strictly prohibited by another. Because escaped aquatic organisms do not recognize political boundaries, a misjudgment by one state that results in introduction into the wild of an invasive aquatic species may ultimate cause ecological and economic harm to other states within the same basin. An example is the situation with Asian carps in the Mississippi River basin, whereby some states permitted wide distribution of some Asian carps whereas other states strictly prohibited these species.

Primary legal authority over importation of potentially invasive fishes in Canada lies within the Department of Fisheries and Oceans (DFO) and Environment Canada; in Mexico this authority resides largely with the Secretary of the Environment and Natural Resources (i.e., Secretaría de Medio Ambiente y Recursos Naturales). The umbrella legislation governing introductions of fishes to the provinces and territories of Canada is the Fisheries Act of Canada (Leach and Lewis 1991). According to Canada's plan to address the threat of aquatic invasive species (CCFAM 2004), efforts to coordinate laws and regulations with a bearing on aquatic invasive species are in their early stages across Canada. Although broad regulatory mechanisms already address the introduction of aquatic invasive species in many cases, enforcement responsibility and funding must yet be addressed. The National Commission for the Knowledge and Use of Biodiversity has created a system of information on invading species in Mexico, including biological inventories, places of origin, vectors of introduction, and negative impacts of the species (Muñoz et al. 2009). With this information in hand, in combination with the risk assessment guidelines developed through the CEC, Muñoz et al. (2009) indicate that it is important to establish policies and rules now for preventing and controlling the introduction of invasive species in Mexico.

8.3.2.2 Best Management Practices

A second strategy for preventing unintentional introductions of invasive species is the development and implementation of best management practices (BMPs). Sets of policies, practices, and procedures, BMPs are designed to reduce unintended consequences from on-the-ground activities. Typically developed by agencies or industries for use by personnel in the field, BMPs can be designed to reduce the unintended introduction or spread of invasive aquatic species. They can also be developed for use by members of the public for activities such as proper cleaning of recreational boats and equipment before leaving a water body infested with nuisance species. There are many examples of BMPs in use to minimize the risk of introducing aquatic invasive species (e.g., Arkansas Bait and Ornamental Fish Growers Association 2002; U.S. Environmental Protection Agency 2008).

Hazard and critical control points (HACCP) planning is a rigorous type of BMP borrowed and modified from the food industry and applied to natural resource work. An international standard (ASTM 2008), HACCP planning is a framework for reducing or eliminating the spread of unwanted species during specific processes or practices or in materials or products. Through HACCP planning specific actions of personnel in the field that incur risk of spreading nonnative species can be identified and then addressed to reduce risk at each of these critical control points. The USFWS encourages the use of HACCP planning and provides training and planning tools on the internet (http://www.haccp-nrm.org).

8.3.2.3 Education and Outreach

A last method employed to reduce the risk of introductions is providing information about aquatic invasive species and nuisance fishes to the public and various user groups through education and outreach. In general, information is provided on the various types of vectors by which species are transported from place to place; steps individuals can take to ensure that they do not accidentally spread species; and the environmental and ecological risks associated with releasing pets, emptying bait buckets, and illegally stocking fishes. There are several active, widespread education and outreach programs targeting particular user groups in the USA to reduce risks of introducing and spreading aquatic invasive species. An important aspect of conducting an education and outreach campaign is crafting a unified message reaching target audiences.

One campaign developed in the USA, sponsored by the U.S. Fish and Wildlife Service and the U.S. Coast Guard, is the program “Stop Aquatic Hitchhikers!”. This program targets recreational boaters in an attempt to educate them on the importance of cleaning recreational boats after leaving an infested water body. Program information is disseminated through a wide variety of outlets, including highway radio messages, billboards, and television, radio, and newspaper advertisements; displays at rest areas; kiosks at retail and other outlets; ads on gas pumps; lawn banners; advertisements in regulations booklets; signs at water accesses; windshield flyers;

displays at airports; brochures; stickers; and other media (Jensen 2008). Another program in the USA, known as "Habitattitude™," is a national initiative developed by the Aquatic Nuisance Species Task Force and its partner organizations, including, among others, the pet industry (see http://www.habitattitude.net/). This program targets aquarium and water garden owners to convey the message that it is not wise to release plants or animals from home aquaria into the wild. The group provides alternative solutions for those who might be contemplating releasing an unwanted pet. This campaign includes in-store signage; brochures; advertisements in newsletters, television, and magazines; bookmarks; pet care sheets; a website; and other media (Jensen 2008). Both Stop Aquatic Hitchhikers! and Habitattitude programs represent broad collaborations among federal and state management agencies and the private sector.

8.3.3 Reduction of Risks Associated with Deliberate Introductions

Stocking of nonnative fishes, primarily for recreational angling, remains a common practice in fisheries management across North America. As of 1995, all continental U.S. states included nonnative fisheries in their recreational fisheries programs, and, primarily due to stocking, approximately one-third of states were home to more nonnative sport fish species than sport fish native to the state (Horak 1995). Widespread stocking is a concern because each stocking event carries risk of unintended consequences (e.g., spread beyond the intended area, stock contamination, or genetic or other detriment to native species). Occasionally, the consequences are substantial. The numbers and distribution of native fishes have been reduced owing to presence of nonnative competitors and predators, and some species have been locally extirpated (Clarkson et al. 2005). Also, because eradication or population control of an introduced species cannot be guaranteed, negative consequences of a deliberate stocking have the potential to be felt for many years to come. Because of the possibility of unintended consequences, it is prudent to consider carefully the ecological and economic risks prior to stocking nonnative species. Over recent decades, most fisheries management agencies have increasingly recognized the risks involved. Multiple symposia and workshops, many sponsored by the American Fisheries Society (AFS), have been published that also address the issue (Stroud 1986; Schramm and Piper 1995; Nickum et al. 2004). In addition, various fisheries journals have devoted entire issues to the subject of fish introductions, impacts, and regulations (e.g., *Fisheries* 1986, volume 11, issue 2; *Canadian Journal of Fisheries and Aquatic Sciences* 1991, volume 48, supplement 1).

Jackson et al. (2004) reported on results of a recent survey administered to U.S. and Canadian fisheries managers containing questions pertaining to stocking practices. Respondents did not indicate a change in emphasis placed on stocking within their jurisdiction from the 1980s through the 1990s compared with the time period since the 1990s. However, 91% of those responding indicated increased justification required to stock fish since the 1990s. Survey results also indicated that trends in agency policies regarding stocking and biodiversity issues changed over recent decades. Only 8 of the 42 (13%) respondents stated that their agencies made decisions not to stock due to biodiversity concerns before 1980. In contrast, between 1980 and 1990, such decisions were made by 37% of respondents, and since 1990, 71% of responding agencies have decided not to stock in order to conserve biodiversity of receiving waters (Jackson et al. 2004). In recent decades, concern over the effect of stocked fish on native fish assemblages and on the genetic integrity of wild fish populations has also grown (Jackson et al. 2004).

Many guidelines exist to aid fisheries management agencies in making stocking decisions (e.g., see articles in *Fisheries* 1986, volume 11, issue 2). Canada has instituted a national set of guidelines pertaining to the movement of aquatic organisms from one water body to another, including, but not limited to, aquatic organisms from fish-rearing facilities (DFO 2003). These guidelines also provide jurisdictions in Canada with a consistent process for assessing potential impacts that may result from deliberate introductions and transfers of aquatic organisms (DFO 2003). The AFS has endorsed a policy statement on introductions of aquatic species (AFS Policy Statement 15; Box 8.1). Some U.S. states follow these guidelines as part of their decision process when considering whether to stock and, if stocking is warranted, how to best proceed. Participants at a recent workshop on the uses of propagated fishes in resource management suggested the following be considered in stocking decisions: ensure stocking activity is part of a comprehensive fish management plan; assess the biological and environmental feasibility of the introduction; complete a risk and benefits analysis and an economic evaluation; seek input from the public; and cooperate with other agencies (Mudrak and Carmichael 2005).

There are also specific actions that can be taken by fisheries managers to reduce the risk that deliberately introduced fishes might adversely affect native species. One such tool is the stocking of sterile fish. Many states require that grass carp stocked for biological control be certified as being sterile (Mitchell and Kelly 2006). State guidelines for appropriate water bodies to stock with nonnative fishes is another means of limiting potential negative impacts of deliberate introductions. It is the policy of the Arizona Game and Fish Department, for example, to allow stocking of nonnative fishes only in waters where native fishes are absent (Rinne et al. 2004). Although potential unintended consequences of stockings are increasingly recognized by fisheries management agencies, the fact that 26% of respondents on a recent survey of fisheries management agencies indicated their agency does not have formal stocking criteria or conditions that must be met prior to stocking cultured fishes (Jackson et al. 2004) indicates that additional improvements are possible.

8.4 ERADICATION AND POPULATION CONTROL

Eradication of invasive species may be a laudable goal but is usually difficult or, in many situations, impossible to achieve. Success depends on a variety of factors, including the type, abundance, and geographic distribution of the targeted species, as well as the physical and biological composition, size, complexity, and sensitivity of the invaded environment. Invasive and other undesirable fish species are abundant and widespread throughout much of North America (Fuller et al. 1999). Few entire populations of an invasive or unwanted fish species have been targeted for eradication, and, among those targeted, relatively few have been eliminated from all locations. This is true in North America as well as in other parts of the world. Nevertheless, because of the increased recognition that invasive species pose a substantial ecological as well as economic threat, eradication remains an important management option. In those cases in which eradication is considered infeasible, management emphasis shifts to controlling or containing the introduced population.

Most successful eradications of nuisance fishes have been in small, easily-accessible, closed aquatic systems (e.g., ponds or small lakes) that are shallow and sparsely vegetated (e.g., Courtenay and Williams 2004; Lozano-Vilano et al. 2006). In more open or complex systems such as large streams or extensive marsh habitats, eradication may be impossible or, at best, difficult

Box 8.1. American Fisheries Society Position on Introductions of Aquatic Species

Below are recommended evaluations to be made prior to introducing nonnative fishes into an ecosystem (taken from American Fisheries Society Policy Statement 15).

Rationale. Reasons for seeking an import should be clearly stated and demonstrated. It should be clearly noted what qualities are sought that would make the import more desirable than native forms.

Search. Within the qualifications set forth under rationale, a search of possible contenders should be made, with a list prepared of those that appear most likely to succeed, and the favorable and unfavorable aspects of each species noted.

Preliminary assessment of the impact. This should go beyond the area of rationale to consider impact on target aquatic ecosystems and general effect on game and food fishes or waterfowl, aquatic plants, and public health. The published information on the species should be reviewed, and the species should be studied in preliminary fashion in its biotope.

Publicity and review. The subject should be entirely open, and expert advice should be sought. It is at this point that thoroughness is in order. No importation is so urgent that it should not be subject to careful evaluation.

Experimental research. If a prospective import passes the first four steps, a research program should be initiated by an appropriate agency or organization to test the import in confined waters (e.g., experimental ponds).

Evaluation or recommendation. Again, publicity is in order and complete reports should be circulated amongst interested scientists and presented for publication in the Transactions of the American Fisheries Society.

Introduction. With favorable evaluation, the release should be effected and monitored, with results published or circulated.

and expensive—and therefore is often not considered. Whether eradication is a viable option depends on many factors including whether reliable plans and methods exist or can be developed, sufficient funding is available, and human resources, including expert leaders and trained crews, are available in addition to other necessary resources (e.g., Donlan and Wilcox 2007).

Eradication and control become more problematic and costly once the targeted population becomes widespread. Consequently, eradication is best attempted almost immediately upon discovery of the new invader population (Simberloff 2009). Unfortunately, many waterways or drainages are not monitored or sampled adequately on a regular basis. For this reason, many nonnative populations are already large and widely dispersed by the time biologists become aware of the invasion. Such was the case with Asian swamp eels, now established in Florida.

Field surveys conducted shortly after their discovery revealed that the geographic range of each of the three known Florida populations was extensive. For instance, Asian swamp eels were first discovered in the Miami area in 1997 (Collins et al. 2002). During the following few years, U.S. Geological Survey biologists sampled connected waterways and found that the invader occupied over 50 km of southeastern Florida canals and concluded, because of its wide distribution and other factors, that the swamp eel was likely present a decade or more prior to their discovery (L. Nico, unpublished data).

8.4.1 Recognition of a New Invader and Determination of Appropriate Action

Successful eradication and control of an undesired or invasive fish species requires basic knowledge of the species and the invaded environment. A critical first step in dealing with a potential introduction is positive identification of the species to confirm the species is nonnative (Fuller et al. 1999). Unfortunately, many fisheries biologists and managers have inadequate knowledge of fish systematics and ichthyology to identify unfamiliar fishes accurately (Courtenay 2007). This phenomenon is not unique to the field of fisheries; the widespread loss of taxonomic expertise has been widely acknowledged (e.g., Agnarsson and Kuntner 2007) and was the impetus for the creation of Partnerships for Enhancing Expertise in Taxonomy, a program that the National Science Foundation continues to fund. Positive identification of foreign organisms may be especially problematic because many are poorly known (Fuller et al. 1999). Following confirmation of a new introduction, rapid but comprehensive field surveys using appropriate gear are needed to determine geographic extent. Armed with the resulting information, appropriate agencies can decide whether eradication is warranted and feasible. If eradication is viable, it is essential to gather basic information on the species rapidly, typically by a combination of literature review and original research. Although a fair amount of data can be gathered during preliminary field surveys, pre-eradication or control efforts may require detailed information on abundance and reproductive status, life history, environmental tolerances, and population dynamics.

Time and effort needed to procure basic biological information depends on the characteristics of the targeted species, characteristics of the invaded habitat, risk that the population will rapidly or easily spread, and potential undesirable effects of the species. Simberloff (2009) argued that successful eradication calls for quick action—in some situations a scorched-earth approach—with minimal time spent conducting research. Nevertheless, Simberloff also recognized that some cases require sophisticated scientific research prior to action. Obviously, a basic understanding of the biology of the targeted fish is necessary in all cases so that the eradication method chosen is appropriate and offers the greatest chance of success.

Each eradication campaign is unique, and problems vary considerably, but those that have been successful share several key elements (Simberloff 2009): (1) early detection of an invasion and quick action to eradicate invader; (2) sufficient resources allocated to the project from start to finish (including posteradication surveys and follow-up, if necessary); (3) a person or agency with the authority to enforce cooperation; (4) sufficient study of the targeted species to suggest vulnerabilities (often basic natural history suffices); and (5) optimistic, persistent, and resilient project leaders.

8.4.2 Methods of Eradication and Control

Methods for eradication and control of invasive organisms can be divided into three categories: chemical, physical, or biological. Some techniques have a long history whereas others are largely experimental or untested. Although there are a wide range of strategies and methods available for controlling unwanted fishes, relatively few have proven useful for eradication. In many instances, an integrated approach is chosen, using multiple methods in combination (e.g., Lee 2001; USFWS 2002; Diggle et al. 2004). A crucial question for eradication is whether the targeted species can be removed at a greater rate than the population grows. Many invasive fishes have high reproductive potentials, and the survival and successful spawning of even one adult pair can potentially lead to thousands of offspring. For this reason, spawning grounds are often a primary target of eradication and control efforts (Diggle et al. 2004).

8.4.2.1 Chemical Methods

Use of fish toxicants (i.e., ichthyocides, piscicides, or fish poisons) is a primary method for eradication or control of undesired and invasive fishes (Marking 1992; Bettoli and Maceina 1996; Wydoski and Wiley 1999; Moore et al. 2008). Some now refer to these chemicals as "biocides." According to Cailteux et al. (2001), as many as 30 different fish toxicants have been used for fisheries management in the USA and Canada, but only three are currently registered for use in both countries. These include rotenone, a widely-used general piscicides (i.e., used for complete fish kills), and TFM (3-triflouromethyl-4-nitrophenol) and Bayluscide (5, 2'-dichloro-4'-nitrosalicylanilide), two chemicals effective against sea lamprey (Smith and Tibbles 1980; Finlayson et al. 2000; Cailteux et al. 2001). Antimycin A (Fintrol®) is another general-use piscicide registered for use in the USA and previously registered in Canada. In the USA, these four chemicals are designated as "restricted use pesticides," and only certified applicators may purchase or supervise their application; however, individual states may have additional requirements regarding use of piscicides (Finlayson et al. 2005). In Mexico the legal status of rotenone and other fish toxicants is less clear. For example, neither Brian Finlayson of California Department of Fish and Game (CDFG) nor the well-known ichthyologist Dr. Salvador Contreras-Balderas (formerly of the Universidad Autonoma de Neuvo Leon, Monterrey, Mexico, personal communication) were aware of instances in Mexico in which rotenone was used to control nuisance fish populations.

According to Rinne and Turner (1991), the scientific literature is "woefully lacking" in documenting the extent, results, and techniques used in many operations using fish toxicants. Even today, most data on the outcome of these types of projects are available only in the gray literature, although many unpublished reports can now be accessed via the internet. In addition, most published papers deal only with projects with successful outcomes (e.g., Table 8.3). Fortunately, updated guidelines for the effective, legal, and safe planning and execution of projects using toxicants are now widely available (e.g., Finlayson et al. 2000; Moore et al. 2008). Of particular value over recent years have been periodic training courses offered by the AFS and other entities for those interested in learning how to plan and execute rotenone and antimycin projects.

Rotenone is a naturally-occurring compound found in the roots of certain plants of the family Leguminosae. It remains the most widely used fish toxicant in control and eradication campaigns in much of the world (Wydoski and Wiley 1999; Cailteux et al. 2001; Clearwater et al. 2003). In North America, rotenone has been used by fish biologists and managers as a

Table 8.3. Summary of selected campaigns conducted in North America to eradicate nonnative fishes, listed in chronological order.

Location	Site description	Targeted taxa	Method	Years	Outcome	Remarks	References
Streams in Craven, Pitt, and Jones counties, North Carolina	14 large coastal streams	Longnose gar	Dynamite	1957	Partial, temporary success	In one day removed 12,707 longnose gars; all or most streams were reinvaded	Johnston (1961)
Leon Creek system, Texas	8 km of small stream and adjacent marshes	Sheepshead minnow and its hybrids	Rotenone and antimycin	1976	Unsuccessful	Subsequent intensive and repeated seining reportedly removed survivors, resulting in success	Hubbs (1980); Minckley and Deacon (1991)
Sinkhole pool, Dade County, Florida	10 × 15 m pool	Black piranha	Rotenone	1977	Successful		Shafland and Foote (1979)
Streams in Great Smoky Mountains National Park, USA	Portions of 5 small streams	Rainbow trout	Backpack electrofishing	1977–1981	Unsuccessful	Target fish were greatly reduced but not eradicated	Moore et al. (1986)
Bylas Springs, Arizona	3 small spring brooks (each 0.2–1 m wide and 2–20 cm deep)	Western mosquitofish	Antimycin	1982	Unsuccessful		Meffe (1983)
Arnica Creek, Yellowstone National Park, Wyoming	Stream drainage, including a 23.6-ha lagoon	Brook trout	Antimycin	1985–1986	Successful		Gresswell (1991)

Table 8.3. Continued.

Location	Site description	Targeted taxa	Method	Years	Outcome	Remarks	References
Susquehanna River, Pennsylvania	Thermal effluent area of electric power plant	Blue tilapia	Temperature manipulation	1987	Partial success	Local population appeared eliminated, but blue tilapia persisted in drainage	Stauffer et al. (1988)
Knife Lake and Knife River, Minnesota	512-ha lake and 113 km of river	Common carp	Rotenone	1989	Successful		Brastrup (2001)
Strawberry Valley, Utah	3,327-ha reservoir, 259 km of stream, and multiple springs	Utah chub, Utah sucker, and other nonnative species	Rotenone	1990	Successful (?)	Targeted fishes reappeared in reservoir, but numbers reportedly remain low; reservoir previously treated with rotenone in 1961	Lentsch et al. (2001)
Frenchman Lake, California	639-ha lake (maximum depth 31m) and tributaries	Northern pike	Rotenone	1991	Successful		Lee (2001)
Streams in Bridger National Forest, Wyoming	3 small streams (1.2–1.6-m mean width)	Brook trout	Backpack electrofishing	1992–1993	Unsuccessful	Population reduced but not eradicated	Thompson and Rahel (1996)

Table 8.3. Continued.

Location	Site description	Targeted taxa	Method	Years	Outcome	Remarks	References
Streams in Great Smoky Mountains National Park, Tennessee	Reaches of 2 small streams	Rainbow trout	Backpack electrofishing	1996–1997	Partially successful	Treatment area consisted of 858 m of stream	Kulp and Moore (2006)
Bighorn Lake, Banff National Park, Canada	2.1-ha (maximum depth 9.2 m) alpine lake	Brook trout	Gill nets	1997–2000	Successful	Naturally fishless lake first stocked in 1965; evidence of reproduction beginning cerca 1980	Parker et al. (2001); Schindler and Parker (2002)
Little Moose Lake, Adirondack Park, New York	271 ha (maximum depth 44 m)—only littoral zone targeted	Smallmouth bass	Boat electrofishing	1998–2005	Successful (temporarily)	Study was conducted to evaluate littoral fish community response to removal of nonnative predator; purpose was not to eradicate entire bass population	Weidel et al. (2007)
Pozo San Jose del Anteojo, Mexico	< 0.1-ha pool	Spotted jewelfish	Traps	2000–2002	Successful		Lazano-Vilano et al. (2006)

Table 8.3. Continued.

Location	Site description	Targeted taxa	Method	Years	Outcome	Remarks	References
Green Pond, Alachua County, Florida	0.2-ha sinkhole	Convict cichlid	Rotenone	2001	Successful	Over 1,000 convict cichlids removed	Hill and Cichra (2005)
Crofton Pond, Maryland	1.6-ha pond (average depth 1.4 m)	Northern snakehead	Rotenone	2002	Successful	8 adult and 834 juvenile northern snakeheads were recovered during rotenone treatment	Lazur et al. (2006)
Diamond Lake, Oregon	1,200-ha lake (maximum depth 16m)	Tui chub	Rotenone	2006	Successful	Previous rotenone treatment occurred in 1954	Truemper (2008)
Lake Davis, California	1,619-ha reservoir (maximum depth 33 m) and tributaries	Northern pike	Rotenone	2007	Successful	Previous rotenone treatment occurred in 1997	Lee (2001); B. Finlayson (personal communication)
Piney Creek drainage, Arkansas	63 km of main stream channel, 660 km of ditches and laterals, and additional shallow standing-water sites	Northern snakehead	Rotenone	2009	Unknown, currently being assessed	Northern smakeheads discovered in drainage in 2008; as of mid-2009 follow-up surveys to assess results not yet completed	M. L. Armstrong (Arkansas Game and Fish Commission, personal communication)

piscicide since the 1930s. Eradication campaigns have targeted a wide diversity of fish species inhabiting a broad range of aquatic habitats, including still and flowing waters (Rinne and Turner 1991; McClay 2005). The first use of rotenone as a fish management tool with intent to eradicate nonnative fishes occurred in Michigan in 1934, an operation involving the removal of common carp and goldfish from two small ponds (Krumholz 1948). Because of the chemical's long history and wide use in fisheries management, there is substantial fisheries literature on rotenone (Wydoski and Wiley 1999; Cailteux et al. 2001; McClay 2005). Over the past several years, the AFS Fish Management Chemicals Subcommittee, rotenone registrants, and the U.S. Environmental Protection Agency have worked on the re-registration process for rotenone. A re-registration eligibility decision was issued March 2007, allowing for continued use of rotenone as a piscicide in the USA. The decision required changes in the label (i.e., written directions for proper use) and preparation of a rotenone standard operating procedure manual, which was recently released (Finlayson et al. 2010). Because information on the environmental effects of rotenone in marine waters is minimal, the new federal regulations will likely permit rotenone use in only freshwater systems unless special approval is obtained.

Antimycin A (antimycin) is a fungal antibiotic whose potential for use as a general fish toxicant was recognized in the early 1960s (Wydoski and Wiley 1999; Finlayson et al. 2002; Moore et al. 2008). The only formulation available for use in North America is Fintrol (Clearwater et al. 2003). It is generally more toxic to fish than is rotenone, and therefore less chemical is needed to achieve similar results (Finlayson et al. 2002). Moreover, at piscicidal concentrations, antimycin does not elicit an avoidance response in fishes, an advantage over rotenone (Dawson et al. 1998; Finlayson et al. 2002). Scaled fish and some rotenone-resistant species tend to be highly susceptible to antimycin, and it has been the piscicide of choice for some native salmonid restoration projects in streams of the western states (Burress and Luhning 1969a, 1969b; Finlayson et al. 2002). Because efficacy depends somewhat on water and habitat characteristics (e.g., pH, water flow, and amount of leaf litter), some fish biologists prefer antimycin for use in small systems and rotenone for larger systems (Finlayson et al. 2002).

Both rotenone and antimycin are general piscicides, but, depending on the water body to be treated and the fish species to be controlled, they have sometimes been used selectively (Lowman 1959; Willis and Ling 2000; Moore et al. 2008). Application of the chemicals typically involves release of diluted liquid solutions directly into the water, although use of powdered rotenone is also common. Some resource managers report success using an ingestible, rotenone-laced feed pellet known as fish management bait to remove grass carp (Mallison et al. 1995). The main advantage cited for antimycin is its effectiveness at lower concentrations and its nondetectability by fish, whereas advantages associated with rotenone are its broad range of toxicity to all species of fish and its effectiveness under a broader range of chemical conditions (i.e., pH) (Finlayson et al. 2002). Rotenone also is presently much less expensive than is antimycin. Both rotenone and antimycin have the benefit of relatively rapid degradation into harmless compounds and both are neutralized by potassium permanganate (Moore et al. 2008). Depending on water temperature and sunlight exposure, degradation may occur within days or weeks with rotenone or within hours or days with antimycin (Dinger and Marks 2007). Depending on concentration, both chemicals can have deleterious effects on aquatic invertebrates. However, because of a shortage of studies, much less is known about the effects of antimycin on these other organisms (Finlayson et al. 2002; Dinger and Marks 2007).

In North America, TFM and the molluscicide Bayluscide have been used extensively since the late 1950s and early 1960s to control sea lamprey in the Laurentian Great Lakes (Heinrich et al. 2003). Both chemicals are nonpersistent in the environment and are nontoxic to other fishes at the low levels used for sea lamprey control. Several different formulations of both chemicals have been developed to treat different habitats of tributary streams and rivers where sea lampreys spawn (Boogaard 2003; Heinrich et al. 2003). In addition, TFM may have the potential to control other nuisance fishes. Boogaard et al. (1996) demonstrated that ruffe were three to six times more sensitive than were native fish species to TFM, but the chemical is currently not approved for control of ruffe.

More than 40 other chemicals have been used as fish toxicants worldwide but have not been fully developed and tested or have not received government approval in North America for use in fish management (Marking 1992; Clearwater et al. 2003; Dawson 2003). One of the more interesting is a diverse group of plant-derived compounds referred to as saponins or triterpene glycosides. Two of the more frequently-cited piscicidal saponins are tea seed cake and mahua oil cake (Clearwater et al. 2003). Dawson (2003) evaluated chemicals known to be used as piscicides and identified Squoxin (1,1'-methylenedi-2-naphthol), a piscicide selective against northern pikeminnows, as a candidate chemical for further development. He also suggested several other chemicals that show promise based on selectivity, ease of application, low toxicity to nontarget organisms, safety to humans, persistence in the environment, low tendency to bioaccumulate, and low cost. Although there is need and continued interest in developing additional piscicides, particularly taxonomically selective piscicides, costs and time associated with research and registration may be prohibitive or, at minimum, preclude their availability in the foreseeable future.

A major drawback with most fish toxicants is their nonspecificity, causing death or harm to nonnative and native fishes as well as to aquatic invertebrates. In some cases, targeted species may have a higher sensitivity to the fish toxicant than do co-occurring native species, thereby allowing some degree of selectivity. However, in many situations the targeted nonnative is either more tolerant (e.g., Asian swamp eels; Schofield and Nico 2007) or has similar sensitivity (e.g., round gobies; Schreier et al. 2008) to many of the nontargeted native fishes present. Consequently, if fish toxicants are used, restocking of native species is typically necessary.

Presence of imperiled aquatic species in an invaded habitat creates special problems. Although a nonnative species may further threaten the imperiled species, use of fish toxicants or other measures to control the invader may also be harmful. Perhaps the greatest reported misuse of a fish toxicant with disastrous results occurred in 1962 when 715 km of the Green River and its tributaries in southwestern Wyoming and northeastern Utah were treated with rotenone as part of a massive fish renovation project (Holden 1991). Because of an inadequate supply of the detoxicant, potassium permanganate, some of the rotenone remained in the river and continued killing fish as it flowed downstream, resulting in heavy losses of native fishes including some imperiled species. It was also suggested that repeated use of rotenone to rid the Little Colorado River of invasive common carp contributed to the disappearance of the Little Colorado spinedace, an endemic minnow (Miller 1963).

Recognizing the need to balance reasonable environmental safeguards with prudent use of rotenone and other fish toxicants, the AFS, in addition to their training course (mentioned above), recently developed and implemented a rotenone stewardship program. Information on rotenone, along with important links, is available via the AFS Web site (www.fisheries.org/units/rotenone/).

8.4.2.2 Physical Methods

A wide array of physical or mechanical methods has been used to control invasive fish populations but have limited potential in eradication (Roberts and Tilzey 1996; Mueller 2005; CDFG 2007). Physical methods include removal of fish by use of nets, traps, gigs and spears, electrofishing gear, explosives, and management of water levels and flows as well as other methods (Smith and Tibbles 1980; Roberts and Tilzey 1996; Wydoski and Wiley 1999).

In general, nets and traps may be useful for controlling nonnative fishes, but eradication is rare and limited to small, isolated water bodies or in portions of drainages. For instance, an intensive seining program conducted during 1976–1978 apparently was successful in completely removing nonnative sheepshead minnow and its hybrids from a small stream system in Texas (Minckley and Deacon 1991). More recently, gill netting was used to eradicate nonnative rainbow and brook trout in high mountain lakes in the Sierra Nevada of California (Knapp and Matthews 1998; Vredenburg 2004) and Banff National Park, Canada (Parker et al. 2001). Small traps were successfully used to eradicate a nonnative fish from a small isolated pool in Mexico (Lozano-Vilano et al. 2006). On the Baja Peninsula of Mexico, removing nonnative fishes from Pozo Largo by means of a variety of nets and traps corresponded with a temporary recovery of an endemic native fish, although it was uncertain if recovery was related to the removals (Ruiz-Camposa et al. 2006). Nonetheless, use of nets to remove unwanted nonnative fishes has also failed to achieve elimination of targeted populations (Neilson et al. 2004).

Researchers in North America have tested backpack electrofishing gear for removal or reduction of nonnative salmonid populations in small upland streams with mixed results (Moore et al. 1986; Thompson and Rahel 1996). A study conducted 1996–1997 in a small southern Appalachian stream showed that four separate removal efforts successfully halted nonnative rainbow trout reproduction and five removal efforts eliminated the species in one reach (Kulp and Moore 2000). In larger or more complex water bodies, electrofishing is less effective. For example, since 2001 biologists have used boat-mounted electrofishing gear several times each year in an attempt to control a large Asian swamp eel population inhabiting a canal system (>15 km long) adjacent to Everglades National Park. In the first year 1,400 Asian swamp eels were captured, but the removal seemed to have little effect on the overall population size or length structure (L. Nico, unpublished data). This removal effort with electrofishing boats has continued and the population appears to have declined. However, as of late 2008, Asian swamp eels remained common in the canal system.

Potential for underwater explosives to kill or injure fishes has been well documented (Teleki and Chamberlain 1978; Keevin 1998). Permit requirements for underwater blasting in the USA and Canada vary considerably among the different states and provinces. A series of experiments determining the efficacy of explosives (dynamite) in removing longnose gar from large coastal streams in North Carolina had limited success and the fish typically recolonized the treated areas (Johnston 1957). Recently, in an attempt to control and eradicate nonnative northern pike in Lake Davis, California, detonation cord was tried but found to be labor-intensive, expensive, and minimally effective (CDFG 2007). There may be considerable variation in blast effects depending on the charge type (e.g., low-velocity versus high-velocity detonation; linear versus point source), charge weight, blast design (e.g., detonation depth), and habitat characteristics (e.g., depth and bottom configuration) (Keevin 1998). Mortality rate and severity of injury may vary between fish species. Fish with swim bladders suffer great harm whereas those that lack swim bladders often survive underwater explosions

(Goertner et al. 1994), indicating some selectivity if explosives are used against certain nonnative fishes.

Fish species exhibit differences in their thermal tolerance limits, but there are relatively few instances in which use of water temperature manipulation to eradicate or control nonnative fish is feasible. In a unique situation, Stauffer et al. (1988) evaluated ways to eradicate a population of blue tilapia in the Susquehanna River in Pennsylvania. Laboratory tests indicated that the lower lethal temperature of the resident blue tilapia population was about 5°C. Because the local wild population in the Susquehanna overwintered in the thermal effluent of the Brunner Island electric power plant, Stauffer and colleagues recommended that the facility temporarily lower the water temperature. In February 1987, electrical output from the power station was purposefully reduced, causing water in the discharge canal to drop below 5°C for at least 25 h. Blue tilapia in the canal were unable to maintain position in the current and were carried into the river. In spring and summer 1987 the canal and adjacent river were sampled, and no blue tilapias were collected. Although the local population appeared eliminated, it was recognized that blue tilapia populations likely persisted in the drainage because of other thermal discharges along the river.

In some instances, water level of a lake or reservoir can be reduced in conjunction with other methods, especially fish toxicants (CDFG 2007). Partial draining is typically performed to reduce the amount of toxicant needed, to increase freeboard above dam so chemical neutralization is not needed, and to contain the targeted fish within a smaller and more exposed area, thereby increasing the chances of eradication. Complete dewatering of a water body to eradicate nonnative fish populations has been proposed for some large reservoirs (CDFG 2007), but in North America complete draining has largely been limited to small water bodies, usually aquaculture ponds (Alvarez et al. 2003; Mueller 2005).

Restoring natural flows in regulated systems has the potential to affect the distribution of nonnative fishes. Impounded systems in California, for instance, tend to be dominated by nonnative fishes, whereas unregulated systems tend to be dominated by native fishes because would-be colonists are regularly flushed downstream (Moyle and Light 1996). In a Mojave Desert oasis, researchers restored natural flow in a small stream thereby promoting recolonization by native fishes while simultaneously deterring invasion and proliferation of nonnative sailfin molly and western mosquitofish, species that prefer lentic habitats (Scoppettone et al. 2005). It was concluded, however, from recent analysis of 19 years of fish assemblage and water flow data from the Gila River basin (New Mexico) that natural flow restoration alone would be unlikely to ensure persistence of native fish assemblages in that system (Propst et al. 2008).

Various barriers have been constructed or proposed for preventing dispersal of nonnative fishes (Hunn and Youngs 1980; Carpenter and Terrell 2005). As with other physical methods, barriers are often used in conjunction with other control or eradication methods. During initial attempts in the 1950s and 1960s to prevent sea lamprey migration, mechanical and screen-type weirs were installed in tributary streams of the Great Lakes (Hunn and Youngs 1980). These included some electromechanical barriers. The barriers provided partial control and an opportunity for design evaluation, but most proved expensive to build and maintain (Smith and Tibbles 1980). Based on attempts to protect a population of Gila topminnows from nonnative fishes, Meffe (1983) concluded that the only sure method of eradication would involve repeated massive applications of antimycin combined with construction of downstream barriers.

Other barriers in use include electricity, bubble curtains, and acoustics, either alone or in combination. The largest electrical barrier project currently operational in the USA is in the artificial Chicago Sanitary and Ship Canal (which connects Lake Michigan to the Mississippi River basin). These barriers have received much attention as a means of preventing Asian carps, present in large numbers in the Mississippi and Illinois rivers, from entering the Great Lakes (Egan 2009). An initial barrier with an expected service life of 3–5 years was activated near Romeoville, Illinois, in 2002 (Conover et al. 2007). A more permanent and more powerful barrier is currently being constructed. A portion of the improved barrier was activated in 2009, amid further safety testing. Barriers have the associated disadvantages of high initial construction costs, continued costs for maintenance, environmental impacts, and the potential to impede native fish migration and movements (Hubert and Dawson 2003).

Increased harvest is often suggested, especially by some members of the public, as a means of controlling invasive or unwanted fishes. This alternative may take a variety of forms, for example, modification of regulations to promote angling and commercial harvesting of targeted species. Increased exploitation may be encouraged by incorporating derbies or by offering bounties (Lee 2001). Unfortunately, because fishes vary in their susceptibility to fishing gears, fishing methods used by anglers and commercial fishers are generally size and species selective. Few small fish are captured by these methods, and many adult fish and some species often evade capture. Consequently, the likelihood of removing an entire population by these methods is extremely low (Thresher 1996). Even if substantial numbers of fish are removed, promotion of angling for or creating commercial interest in an invasive fish may also increase the risk that humans will illegally transport the invasive fish to other water bodies (Fuller et al. 1999).

During the 1960s the blue tilapia was introduced into Florida waters and spread rapidly. An early attempt to eradicate the blue tilapia was unsuccessful (Buntz and Manooch 1969; Hale et al. 1995). Over recent years a major commercial fishery for blue tilapia developed in Florida (Hale et al. 1995), but these nonnative cichlids remain abundant and widespread.

8.4.2.3 Biological Methods

A variety of biological methods have been attempted or proposed to eradicate or control unwanted fishes. Release of predatory species to prey on undesirable or invasive species has a long history although it is not particularly common in the fight against invasive fishes. One of the more unusual attempts occurred in 1891 when authorities released 19 sea lions into Lake Merced, California, to prey on and eliminate the reservoir's large common carp population (Smith 1896). In south Florida, predatory South American butterfly peacock bass were stocked into canals to control spotted tilapia and other nonnative cichlids (Shafland 1995). This was judged to be a biological success by some (Shafland 1995; Thresher 2008), but introduced cichlids remain abundant and several new nonnative fishes (e.g., Asian swamp eels and bullseye snakeheads) have colonized canals already occupied by butterfly peacock bass (Collins et al. 2002). Release of nonnative and native predators to control other nonnative fishes also may result in unintended consequences (Moyle et al. 1986), such as stressing native prey fish species. This was the outcome of stocking additional predators to control ruffe in Lake Superior (Mayo et al. 1998).

There is a potential for use of contagious diseases (e.g., koi [common carp] herpes virus, or KHV) to control invasive fishes, but this alternative is highly controversial because of the potential to harm related desirable species (Gilligan and Rayner 2007) and difficulty in correcting any unintended consequences from the introduction. Moreover, it is likely that surviving fish would have immunity to the disease, rendering the method useless after one application. Still, the use of contagious disease could be helpful in combination with other methods.

More technologically advanced biological methods have promise but, with the exception of the release of sterile males to help control sea lamprey in the Great Lakes, these methods remain largely untested in controlling nuisance fish populations. The two main genetic manipulation techniques proposed include (1) chromosome set manipulations involving production and release of triploid sterile nonnative fish with the intent of reducing the population size of targeted naturalized individuals; and (2) recombinant DNA methods involving transgenic techniques designed to produce sterile fish or spread deleterious transgenes (i.e., "Trojan horse" genes) to a target nonnative species (Kapuscinski and Patronski 2005; Gilligan and Rayner 2007; Thresher 2008). In North America, the only field application using a genetic strategy to control an invasive fish involves the annual release of chemically sterilized (by injection with bisazir [P,P-bis(1-azirindinyl)-N-methylphosphinothioic amide]) male sea lamprey into the Great Lakes (Heinrich et al. 2003; Bergstedt and Twohey 2007). This method has been shown to contribute to the sustained reduction of sea lamprey in that ecosystem (Twohey et al. 2003). Researchers in Australia have been interested in use of "daughterless genetic technology" to combat introduced fishes, especially common carp. This genetic technique involves creating a heritable gene that suppresses the production of female offspring thereby causing a reduction in the nuisance population over successive generations (Gilligan and Rayner 2007). Recently U.S. Geological Survey scientists began investigating use of daughterless and under-dominance inheritance as a possible method to control Asian silver and bighead carp populations in North America (King 2009).

Production of genetically-modified food fish within the aquaculture industry has become increasingly common (Howard et al. 2004). In contrast to the use of this technology for biocontrol purposes, commercially-desirable species are genetically manipulated to increase their fitness and, therefore, many scientists are concerned that the resulting engineered fish, if released to the wild, will cause substantial ecological harm (Howard et al. 2004). Numerous concerns exist regarding field application of genetic strategies proposed for control of invasive fishes, and decisions will likely require wide government, scientific, and public approval.

One of the more promising and possibly most benign biological control methods in development is use of pheromones, natural chemicals secreted by many fish and important in influencing their behavior (Sorensen and Stacey 2004; Fine et al. 2006). To date, most laboratory and field application of pheromone techniques have been directed at control of sea lamprey in the Laurentian Great Lakes (e.g., Teeter 1980; Li 2005). Wagner et al. (2006) conducted field tests and demonstrated that pheromone signals were highly effective as attractants in trapping migrating sea lampreys. Even chemically-sterilized males release a sex pheromone that attracts ovulating females (Siefkes et al. 2003). Use of pheromones in sea lamprey control would have the added benefit of reducing reliance on the effective but costly fish toxicants such as TFM.

8.4.3 Past Eradication Campaigns: Successes and Failures

Attempts to eradicate nonnative fish populations in North America have had widely mixed results (Minckley and Deacon 1991; Rinne and Turner 1991; Cailteux et al. 2001). Generally, invasive species are more difficult to eradicate from larger water bodies than from smaller ones (but see Meronek et al. 1996). Most documented successful eradication projects have relied entirely or heavily on the use of rotenone. Nevertheless, a substantial number of eradication projects involving application of rotenone fell short of eradication. Some of these failures are likely explained by poor planning or project implementation rather than rotenone being a poor choice. Rinne and Turner (1991) reviewed past efforts using fish toxicants to remove or eradicate various unwanted fishes from western streams of the USA. Among 26 such projects for which results were provided, 9 (35%) were considered successful, 15 (58%) were listed as either unsuccessful or failures, and 2 others were judged as being a short-term success or of variable success. Among 51 projects reportedly designed to eliminate one or more target fish, Meronek et al. (1996) judged 32 to be successful. However, the Meronek et al. definition of success did not necessarily mean eradication.

Table 8.3 provides a summary of a few recent campaigns in North America to eradicate nonnative or other undesirable fishes. Examples include a range of targeted species and different small and large bodies of water. Following is a brief review of two projects, one an example of a small project in Mexico using traps and the other a large project in California.

In 1996, the African spotted jewelfish was discovered in a natural clear-water pool known as Pozo San Jose del Anteojo in the Cuatro Ciénegas valley of northern Mexico (Lozano-Vilano et al. 2006). The region is home to a number of endemic native fishes and there was evidence that native species in the pool had greatly declined following appearance of the invasive fish. To eradicate the invasive fish, minnow traps were deployed, resulting in removal of over 19,000 spotted jewelfish over the course of 3 years (2000–2002). The invaded water body was quite small (28-m wide, 0.8-m deep), and follow-up trapping indicated the eradication effort was probably successful, although researchers noted continued monitoring of the site.

One of the more recent large-scale attempts to eradicate a nonnative fish population occurred in California (Lee 2001; CDFG 2007). In 1994 northern pike was discovered in Lake Davis, a large artificial reservoir covering 1,600 ha with a maximum depth of 33 m at full pool (see Box 5.5). After substantial planning and various attempts to reduce the northern pike populations by means of nets, electrofishing gear, and other fish capture devices, a decision was made to apply rotenone to the lake and its tributary streams. In the early 1990s, the CDFG had already had success using rotenone to eradicate northern pike from nearby Frenchman Lake, another large and deep lake. The Lake Davis project faced considerable public opposition, especially because of fears that the domestic water supply would be harmed. The CDFG received the necessary permits and cleared the legal challenges in late 1997, and rotenone treatment of the lake began in mid-October of that year (Lee 2001). Despite delays and a few technical difficulties, the 1997 Lake Davis operation initially appeared to be a success, with toxic concentrations of rotenone throughout the lake for several weeks (Siepmann and Finlayson 1999). However, 2 years later northern pike were rediscovered in the lake. It remained unclear whether the 1999 fish were survivors of the 1997 treatment or had been illegally reintroduced (Lee 2001; CDFG 2007). Following rediscovery of northern pike, several years were spent attempting to control and contain the fish without use of piscicides. This included use of explosives (i.e., primacord), a variety of nets, and electrofishing boats. Although the strategy removed large numbers of northern pike, the population continued to increase in size. By that time the public better understood the various threats posed by presence of northern pike. With the added benefit of public support, CDFG developed plans for executing a second rotenone application. Rotenone treatment of the lake and tributary streams occurred in September 2007 and, based on the presence of toxic rotenone concentrations throughout the lake (McMillin and Finlayson 2008) and the absence of northern pike in subsequent fish samples (into 2009), the second rotenone treatment has been considered a success. According to Brian Finlayson (personal communication), state biologists and resource managers learned much about how best to prepare for and conduct rotenone projects as a result of problems that arose during the first Lake Davis treatment.

8.4.4 Research Needs

Throughout North America there is a need for improved methods to eradicate or control nuisance fishes. The need is especially great in situations where introduced fishes are causing the decline of endemic or imperiled native species (Ruiz-Camposa et al. 2006). Future research will likely be devoted to the control or eradication of a few of the more notorious invasive and undesirable species. However, many of the techniques and strategies developed in combating one species can be applied to other undesirable taxa. Future needs include reexamination and adjustment of certain methodologies, such as using currently registered piscicides to greater efficacy. There is also the need to develop and test other chemicals that may be more selective and less harmful to nontarget species. Use of newer biological techniques, including Trojan genes and pheromones, may permit future biologists and resource managers to be highly selective in targeting fish and other aquatic species for removal. Unfortunately, it is likely that many of these advances will be costly to develop, and field applications are decades away.

8.5 INTEGRATED PEST MANAGEMENT

No “silver bullet” exists to prevent or control the introduction or spread of nuisance fishes. Management takes many forms and may, depending on the goal, be aimed at preventing the initial introduction, controlling populations already present, or eradicating established populations. Appropriate management actions and their likelihood of success depend on a variety of factors, including the number and types of introduction vectors, characteristics of the undesired species (e.g., population size, life history, and habitat needs), characteristics of the ecosystem (e.g., habitat available, size of the area invaded, accessibility for application of management measures, and physiochemical characteristics), and a variety of human influences (e.g., willingness to regulate or to apply control measures and economic feasibility). These factors vary not only among species considered for prevention and control measures but also within one species across a variety of human and wild landscapes. Likewise, effective management alternatives appropriate for a given situation depend on whether the species has already been introduced or is newly established, spreading, or already widespread. Successful prevention and control of nuisance fishes often use an approach that identifies and combines all viable management alternatives into an integrated management framework.

8.5.1 Integrated Pest Management: What is it?

Integrated pest management was originally developed out of the need to control agricultural pests and became formalized into a cohesive strategy around the late 1950s (Forney

1999). The beginnings of IPM, however, can be traced to the late 1800s when ecology was identified as the scientific foundation for plant protection (Kogan 1998). Although founded in agriculture, IPM has been applied widely. For example, IPM has been used in shrubs and trees used as landscape plants (Raupp et al. 1992) and to control reed canarygrass (Kilbride and Paveglio 1999), white-tailed deer (Coffey and Johnston 1997), and sea lice on farmed salmonids (Mordue and Pike 2002).

The approach taken by IPM is to incorporate the best management options and control tools available into an overall management plan with the goal of restricting, reducing, and maintaining the target species at levels of insignificant impact while minimizing danger to the environment, human health, and the economy (Hart et al. 2000). Traditionally, therefore, the goal of IPM has to maintain pest populations below nuisance levels (Smith and Reynolds 1966; Dent 1995); however, applying IPM to eradicate targeted pest populations is intuitive, and some management plans with eradication as a goal have proposed IPM (e.g., Asian carps in the Mississippi River drainage; Conover et al. 2007).

8.5.2 Development of an Integrated Pest Management Strategy: Fitting the Pieces Together

A focused IPM strategy begins with determining the type and form of IPM system needed to achieve the desired level of control (Dent 1995). According to Hubert and Dawson (2003), the process is guided by answering a series of questions: (1) who will be using the IPM control techniques? (2) on what scale will the program be implemented? (3) what control measures will be used? (4) how will the control measures be applied? (5) what are the perceived benefits? and (6) over what temporal scale will benefits be realized?

Substantial information must be collected prior to developing an IPM strategy, beginning with detailed information on site conditions and complexity of the system. As thorough an understanding as possible of the current and potential distribution and the life history and ecology of the targeted species, as well as the biology and distribution of sensitive or important nontarget species, is also needed to determine which control measures should be included in the IPM strategy and to identify life stages most appropriate to target for individual control methods. Managers must also consider the economic resources available to tackle the problem, understand the likelihood and severity of undesirable effects of no action as well as understand the likelihood and severity of unanticipated negative effects of the proposed management actions, and work with relevant management authorities to develop common goals and determine responsibilities. It is also important to include all management authorities in developing and implementing an IPM strategy, with input from all stakeholders regarding the managed resources. Greater involvement by outside agencies and entities better ensures that management goals remain relevant and encompass all appropriate resource uses. Integrated pest management requires a more multidisciplined approach than does traditional natural resource management, and logistics of implementing IPM strategies are often not trivial and require specialized personnel training.

Because IPM is typically seen as a longer-term commitment rather than a quick fix, it should not be seen as a stagnant process. Developing and implementing the optimal IPM strategy functions best when practiced iteratively—when the outcomes of management actions are monitored, the results are evaluated, and management actions are adjusted on the basis of what has been learned from previous management efforts. Thus, IPM is improved by adaptive management, a structured, iterative process used to make optimal decisions in the face of uncertainty (See Chapter 5; Holling 1978; Walters 1986).

Another important component of IPM is educating the public not only about the negative effects of nonnative and nuisance fishes but also about the types of control being implemented and potential effects of control efforts. In some cases, public involvement in controlling nuisance fishes has been incorporated into management plans in the form of bounties and encouragement to increase harvest. Many educational materials that target a variety of audiences are available from federal, state, and nongovernmental organizations for this purpose.

With the realization that nonnative and nuisance species do not adhere to jurisdictional boundaries the most effective IPM strategies are developed at a scale sufficient to address the problem. In many applications, this approach may encompass at least the watershed to be managed, but the strategies could be adjusted to regional or larger scales if necessary to achieve greatest effect. Overall, IPM is a holistic approach that seeks to improve management by promoting the exchange of all types of information regarding problems associated with the nuisance fish population and the implemented control actions; allows for increased sharing of data generated from monitoring and control efforts; and aids in developing and communicating a common message across agencies and partners from the public and other entities. One of the best examples of a large-scale program to control an invasive animal that uses IPM as a foundation for success, outside an agricultural context, is the sustained control of sea lamprey in the Great Lakes (Christie and Goddard 2003). This control program exemplifies some of the benefits of IPM: it has a basis in research to discover life stages most vulnerable to control; it continually seeks to develop new and improve existing control techniques; it looks to minimize effects of control on native and desired species; it efforts to minimize environmental impacts of control measures; and it continues to develop efficiencies in research, monitoring, control, and information sharing by extensive use of partnerships. See Box 8.2 for a detailed description of the sea lamprey control program in the Great Lakes.

8.6 CONCLUSIONS

In general, it is society, sometimes in the form of natural resource management goals, other times in the form of irate anglers and members of other user groups, that decides which fish populations are a ”nuisance.” Moreover, society’s perceptions can change considerably over time. Management goals and the methods used to achieve them, therefore, typically do not remain static. Decisions made a century ago to develop or enhance recreational fisheries by liberal stocking of nonnative fishes are judged differently today. Management agencies are more aware of uncertainties associated with deliberate introductions, although stocking fish for recreational and other purposes is still widely practiced throughout North America. Still, it is apparent that today’s resource managers have learned from earlier introductions gone awry, and there is a discernible trend toward greater consideration being put into recent stocking decisions. Moreover, continued interest among fisheries managers to reduce risks associated with deliberate introductions indicates that this trend is likely to continue. Likewise, federal, state, tribal, and other management entities, as well as the public, have greater awareness of the unintended consequences that can result from introductions (whether accidental or deliberate). Development of new tools to identify potentially invasive species and risky vectors of introduction demonstrate this greater awareness. New legislation and

Box 8.2. Sea lamprey in the Great Lakes

The campaign to control sea lamprey in the Laurentian Great Lakes has been long, intensive, groundbreaking, successful, and expensive. More than five decades of research and management have been devoted to combating this invasive fish species. Research continues today to fine-tune control techniques in use for decades; to make better decisions about how, when, and where to apply control measures; and to explore new methods using genetic manipulation and pheromones to exploit weaknesses in sea lamprey biology further.

The sea lamprey is a primitive and jawless fish that as an adult is a parasitic predator on larger fish. It is an anadromous species, native to the Atlantic Ocean and spawning in streams along the Atlantic coasts of Europe and the USA. Although native to Lake Ontario (Bryan et al. 2005), modifications to the Welland Canal in 1919 allowed passage of sea lampreys to Lake Erie from Lake Ontario (Christie 1974). By the 1940s, sea lamprey flourished in the upper lakes, drastically reducing the abundance of lake trout, lake whitefish, and cisco populations (Christie 1974). Commercial catches plummeted, and lake trout were eliminated from all of the Great Lakes except for Lake Superior (Elrod et al. 1995). In response to the collapse of commercial fisheries, the governments of the USA and Canada created the Great Lakes Fishery Commission (GLFC) in 1954 with a goal of controlling sea lamprey in the Great Lakes (Kolar et al. 2003). Ashworth (1987) provides a good review of the invasion of sea lamprey into the Great Lakes.

The GLFC began searching for a selective piscicide that could be used to target sea lamprey at the larval stage, when larvae burrow in sediments of small streams for between 5 and 7 years (Kolar et al. 2003). Over 6,000 chemicals were screened, and sensitivity to nitrophenols was discovered (Applegate et al. 1958). Eventually TFM (3-trifluoromethyl-4-nitrophenol) was identified as being selective for sea lamprey (Applegate et al. 1961). A control program evolved based on the application of TFM to streams with larval sea lamprey. Wounding rates (fresh wounds and scars from previous sea lamprey attachment) of stocked lake trout began to decline and abundance of lake trout increased (Kolar et al. 2003). Chemical treatments have been applied to natal streams of sea lamprey in the Great Lakes basin every year since. Even though suppression of sea lamprey populations to 10% of peak abundance through time was achieved, it became apparent that eradication of the species was unlikely and a longer-term control program was developed. As concerns about release of chemicals into the environment grew, the GLFC began to search for other means by which to control sea lamprey. As early as 1980, an integrated pest management approach was suggested for sea lamprey (Sawyer 1980). This concept provided the framework that the GLFC used to develop its integrated management of sea lamprey policy (Davis et al. 1982).

The integrated management program developed to include several different types of control, though chemical application remains important today. An excellent synopsis of the program can be found in Christie and Goddard (2003). In addition, over 800 pages of research articles dedicated to the biology and control of sea lamprey can be found in a 2003 special issue of the *Journal of Great Lakes Research* (volume 29, supplement 1). Current sea lamprey control techniques include applying chemicals (TFM formulations,

(Box continues)

Box 8.2. (Continued)

as well as several formulations of niclosamide [2′,5-dichloro-4′-nitrosalicylanilide], another chemical that selectively kills larval sea lamprey), trapping and removing adults that return to spawn, releasing chemically sterilized males (sterilized by injection with bisazir) to compete with fertile males for spawning females, and deploying physical barriers of various types (mechanical and electrical) to interfere with migration to spawning habitats. Promising new control techniques using pheromones are under evaluation. These techniques affect migration and spawning behaviors of sea lampreys to increase capture efficiency and reduce spawning success (Christie and Goddard 2003; Li et al. 2003; Sorensen and Vrieze 2003). There is also hope that genetic and molecular techniques may be added to the tool chest to manage sea lamprey in the Great Lakes (C. Goddard, GLFC, personal communication).

Sustained control of sea lamprey in the Great Lakes has allowed for revitalization of the commercial and recreational fishery in the Great Lakes, estimated to be worth over US $7 billion annually (Anonymous 2008). The program is successful because of a multitude of factors: realization that successful management of the species would require participation by all fisheries management authorities among the Great Lakes, resulting in formation of the GLFC; study of the biology of sea lamprey and identification of a vulnerable life stage for control; identification and development of a selective chemical agent; use of an integrated management approach that develops and adds new control techniques as they become available; continual funding of research on the biology and control of sea lamprey; management and decision-making infrastructure provided by the GLFC; and sustained social and political will to continue control. At an annual cost of approximately $20 million (M. Gaden, GLFC, personal communication), the sea lamprey control program offers a success story as well as a warning: even for those few species for which specific control measures can be developed, prolonged control comes at substantial economic cost. Therefore, preventing the introduction of nuisance species into additional areas is usually the most cost-effective means of control.

regulations addressing this concern, development of new BMPs, monitoring and reporting networks, and national management plans for particular species of concern further indicate that we, as a society, are more informed and looking to reduce unintended consequences of our actions. Perhaps these concerted efforts portend a brighter future, one with fewer nuisance fish populations and, as a result, less of a need to spend valuable time and resources on eradication and control efforts.

The situation with nonnative fishes is dynamic. Many nonnative fish populations already present will persist, and some will become more abundant, invade new areas, and cause ecological and economic harm. Almost certainly, new introductions will occur, some involving species not currently in the pathway and presenting unique problems. Some nonnative fishes will be viewed as benign and others as nuisance. Certain native fish populations may also expand, impinge on meeting management goals, and thereby also earn the tag of nuisance species. Given this scenario, it is almost certain that nuisance fishes and other aquatic organisms will continue to pose challenges for natural resource managers far into the future. Aquatic ecosystems, because of a limited number of approved control methods and ecosystem complexity and connectivity, offer unique obstacles to implementation of effective management. Global changes such as changes in land and water use and human population growth will affect the distribution, habitat, and management of undesired fishes in North America, presumably often in unforeseen and complex ways. Most introduced species currently established in inland waters of North America exist mostly in what have been considered warm-to-cool temperate areas. With climate change, currently established introduced species can be predicted to expand their ranges in coming decades. Climate change was not a factor considered when past introductions were made, so the full effects of those earlier introductions may not yet have been realized. Consideration of the implications of climate change as well as other global change drivers should be incorporated into current and future fisheries management plans.

To deal with these challenges better, fisheries managers should work toward (1) managing at an appropriate scale, encompassing at least the entire watershed area inhabited by the nuisance species whenever possible; (2) developing IPM strategies after collecting baseline information and carefully considering all control and eradication options and enlisting participation from all relevant partners and management agencies; (3) managing adaptively through time to incorporate lessons learned from past efforts; (4) keeping abreast of and implementing new developments in monitoring, early detection, control and management, and information sharing as appropriate; (5) making concerted efforts to educate and inform individuals, groups, industries, and other entities about risks of introducing aquatic species associated with human activities; and (6) being cognizant of global changes that may be affecting the management area.

Additional research in several key areas might give fisheries managers much needed tools to better combat nuisance fishes. Often nuisance fishes are not discovered until they have already become numerous, have spread to a large area, or both. New methods to detect newly introduced or established nonnative fishes would increase opportunities for successful eradication. Once a species is detected, deciding the appropriate course of action would be improved if more were known about which introductions carry the highest risk to the environment and the economy. Further research in screening and risk assessment techniques and tool development would aid the field of fisheries management. Once it is decided to proceed toward eradication or control, there are many methods from which a manager has to choose. However, there is ample room for improving these existing techniques, and the need to develop additional tools for controlling aquatic species remains great. Lastly, managing nuisance fishes would be better informed by research in the social sciences. Understanding human behavior as it relates to risks of spreading aquatic species unintentionally, factors affecting the decision to liberate animals into inland waters, and natural resource use patterns to assess vectors of introduction better and identifying the most effective means of educating user groups about potential risks would all improve management efforts.

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