Chapter 9

Use of Hatchery Fish for Conservation, Restoration, and Enhancement of Fisheries

JESSE TRUSHENSKI, THOMAS FLAGG, AND CHRISTOPHER KOHLER

9.1 INTRODUCTION

Aquaculture is the propagation of aquatic organisms under circumstances that facilitate greater productivity than would be observed in a natural setting. In terms of tangible resources and labor, culture methods and inputs vary from extensive (little effort or resources expended, minimal confinement of animals) to semi-intensive (pond production, limited input such as provision of supplemental feed or pond fertilization to enhance zooplankton productivity) to intensive (indoor production in tanks or raceways, provision of complete formulated feeds). Culture of finfishes, herein referred to as fish culture, is conducted for differing purposes, but most fish are raised for direct consumption as food fish or for stocking into natural habitats. Ornamental fishes are also cultured for the pet and aquarium trades. The approach taken by fish culturists differs among these scenarios with respect to production goals (rapid growth and food conversion efficiency versus genetic diversity and reproductive success in the wild) and specific culture methods (intensive production, high densities, and high performance feeds versus lower densities, reduced exposure to habituating elements, seminatural habitats, and predator avoidance and foraging training).

The approach undertaken to produce hatchery fish varies by management strategy. Stocking programs are implemented when increasing the number of fish in a population is desired, but the underlying reasons for increasing population size, and thus the preferred characteristics of the fish, will differ from one situation to the next. Selection of broodstock and day-to-day husbandry techniques can influence population genetics, individual behavior, and the ultimate success of propagated fishes in the wild. Misconceptions about the practice of fish culture and mismatch between the means (hatchery operation and culture techniques) and the ends (management objectives) of using propagated fishes in fisheries management has fostered some criticism of fish culture and hatchery fish. However, increased communications among culturists, geneticists, fisheries managers, and other stakeholders have supported development of best management practices for fish culture and an age of hatchery reform. In this chapter, a general description of fish culture practices is provided, how propagated fishes can be used to meet fisheries management objectives is described, and recommendations to improve the success of stocking programs under various management scenarios are given.

9.1.1 Agency Goals and Public Pressure

Fish stocking has long been an important tool used by natural resource agencies to manage a variety of fisheries. Accordingly, agencies have established fish production programs relying on state, provincial, or federal hatchery facilities to meet their stocking needs (Heidinger 1999; Hartman and Preston 2001; Halverson 2008). The extent to which recreational fisheries rely on stocking programs varies among states and provinces and with the type of water body. In the state of Michigan, for example, 40% of all recreational fishing depends on stocked fish, with at least 70% of the Great Lakes' trout and salmon fishery resulting from stockings. Agencies are mandated to manage waters in their purview for the betterment of the resource and to meet the needs and demands of the public. Management plans are developed by fisheries management professionals and are guided by information gleaned from population assessments and other surveys, as well as pressures exerted by the fishing public. Recreational fishing is often an overriding factor in this regard and, in many cases, stocking programs become essential, if only from a public relations standpoint. Thus, stocking programs have biological, ecological, and political underpinnings. When political considerations have an overriding influence, the ends and means of the stocking program may not be based on the best available science. Public hatcheries operate to meet the needs of the agency's stocking plans, and hatchery professionals often have little input into why, where, or how the fish they raise are stocked. However, hatchery reform and increased communications among fisheries biologists, managers, culturists, and their respective oversight bodies are refining the process of fish culture to support stocking programs that better suit stakeholder needs and management objectives.

9.1.2 Roles of Individuals and the Private Sector

A majority of hatcheries and stocking programs are operated in the public sector; however, it is important to recognize that private individuals and organizations, including commercial and nonprofit groups, may also be involved. Propagation programs are often initiated by government agencies to support stocking efforts for public benefit (e.g., to improve commercial or recreational fishing opportunities or to restore imperiled species). Once the programs are well developed, individuals and the private sector may also become engaged in the production of fish for the public good. In these cases, the public sector will often retain responsibility for technical aspects of propagation and rely on the private sector for practical matters (Lorenzen et al. 2001). For example, Alaska's "ocean ranching" efforts are largely supported by private nonprofit hatcheries operating with public agency oversight (Heard 2003). Canada's Salmon Enhancement Program (SEP) includes provisions for Public Involvement Project (PIP) hatcheries operated largely by community volunteers: of the approximately 174 million fish released under the SEP umbrella in 2002, roughly 10% were produced in PIP hatcheries (MacKinlay et al. 2005). Alternatively, natural resource agencies may simply purchase fish for stocking from private producers or public hatcheries may produce fry and fingerlings and then contract with private aquaculture operations to grow them out to preferred stocking sizes. Increasingly, fish culture, even for the purpose of public benefit, is represented by individuals and groups from the private and public sectors.

9.1.3 A Word regarding Terminology

The term “introduced fish” takes on a number of meanings because it has both geopolitical and ecological connotations (see Chapter 8). In fisheries management, it is often used whenever a species is stocked into a system where it did not previously exist. It could be a transplant (i.e., moved within its native distribution) or an exotic (i.e., moved from outside its native distribution). However, some species have been stocked so widely across North America (e.g., largemouth bass, rainbow trout, and striped bass) that “native distribution” has little meaning beyond a historic context. In all practicality, the term “exotic” is most often used to refer to a species originating from another continent (e.g., Asian carps, zander, and tilapias).

9.2 STOCKING PHILOSOPHY

There are numerous reasons for stocking fish as part of a comprehensive program to manage public waters (Noble 1986). New or newly-renovated waters usually require an introductory stocking of appropriate fish species. For example, a new reservoir might be inhabited by riverine species existing in the drainage prior to impoundment, but these species are often poorly suited to the newly created, lacustrine environment. Likewise, farm ponds and other small impoundments must initially be stocked with appropriate assemblages (see Chapter 16). In some states, such as Illinois, state hatcheries will provide largemouth bass, sunfishes, and channel catfish for the initial stocking of newly constructed or renovated farm ponds.

Many stockings are conducted as “value-added” fishery augmentations to increase or diversify recreational fishing opportunities. Stockings often serve the purpose of filling voids. This might include stocking a fish species such as striped bass to establish a pelagic fishery or flathead catfish to create or augment the benthic fishery. Another management goal of value-added stocking may be to establish trophy fisheries for popular sport fish such as muskellunge.

Although some fish are stocked in the hope of increasing recruitment, other stockings take place with no expectation of establishing a self-sustaining fishery. For instance, many reservoirs in warmer climates support “two-story fisheries” for rainbow trout, wherein cool, deep waters provide refuge when temperatures above the thermocline are too warm. Rainbow trout grow well in many reservoirs but are unlikely to find sufficient suitable habitat in reservoirs to spawn and create a self-sustaining population. Harvest and natural mortality in these fisheries are compensated through routine supplemental stockings. Another example of a stocking-dependent, “put-and-take” fishery is stocking catchable-size coldwater species such as rainbow trout into warmwater streams in the late fall. In this case, the goal is to create an intermittent fishery in which nearly all stocked fish are returned to the creel before rising water temperatures cause mortality in the spring.

Anadromous species (e.g., salmonids or striped bass) and interspecies hybrids (e.g., saugeye, tiger muskellunge, and hybrid striped basses) are often stocked with little expectation of establishing self-sustaining populations, though some have occurred. For example, several species of anadromous salmonids have become established in Japan (coho salmon), Patagonia (brown trout, rainbow trout, and Chinook salmon), New Zealand (sockeye salmon and Chinook salmon) and in various locations outside their normal distribution in North America (pink salmon in Maine; pink salmon, coho salmon, and Chinook salmon in the Great Lakes); however, in some instances, the species became established by developing land-locked life histories (Pascual and Ciancio 2007). Striped bass, introduced to California in 1879, became established in the San Joaquin River estuary system and once supported large sport and commercial fisheries (Stevens et al. 1985). In the case of interspecies hybrids, such as hybrid striped basses (various crosses of *Morone* species, e.g., white bass × striped bass), natural reproduction is observed but contributes little to recruitment (Avise and Van Den Avyle 1984).

Even when natural reproduction occurs, the size of the breeding population or recruitment may still be insufficient to support a self-sustaining population. Supplemental stockings are often necessary to overcome habitat modifications or limitations, intense harvest, or a combination of anthropogenic effects. In circumstances where habitat or environmental quality is unlikely to be restored, routine supplemental stocking may be required. In these situations, poor recruitment is compensated by stocking juvenile fish with the expectation they will grow to a size to be caught by anglers or commercial fishers. These are called "put-grow-take" fisheries. For example, species such as walleye and northern pike may be able to spawn in reservoirs, but limited nursery habitat often results in poor year-classes in the absence of supplementation. The salmonid stocking programs of the Pacific Northwest, sometimes referred to as ocean ranching, are another example of supplemental stocking used to compensate for high fishing mortality and restricted access to spawning grounds. Fish stockings may also be necessary following natural or, more likely, human-induced fish kills. It is also not uncommon for electric utility companies to establish hatchery facilities to stock fish routinely to mitigate losses resulting from their operations (e.g., intake impingements or thermal pollution from discharges). Supplemental stocking of prey species (e.g., threadfin shad or mysid shrimp) is another means to augment established fish populations that may be underperforming due to inadequate prey availability. It should come as no surprise that the concept of predator–prey balance is often blurred in systems receiving the dual anthropogenic forces of stocking and high fishing mortality.

Fish may also be stocked as biological controls of undesired organisms. Examples include stocking western mosquitofish or fathead minnows for mosquito control and grass carp for control of aquatic nuisance plants. Large piscivores, such as muskellunge, may be introduced to control large-bodied prey species. Piscivores may also be stocked as part of "biomanipulation" strategies to enhance water quality (Lathrop et al. 2002; Mehner et al. 2002) or to enhance fishing opportunities (Neal et al. 1999).

Propagation and stocking programs also play an important role in enabling the recovery of rare or endangered fishes (Johnson and Jensen 1991). In most cases, federal hatcheries are responsible for undertaking these efforts. These hatcheries serve as refugia, sites to conduct controlled research, and as sources for re-introductions or supplemental stockings of imperiled fishes (see section 9.3.3).

9.3 HATCHERIES AND APPROACHES TO FISH CULTURE

Hatcheries can be generally categorized according to operational strategies geared to various production goals and stocking philosophies discussed above. Production, supplementation, and conservation hatcheries have distinct directives that shape how they function and influence the physical, genetic, and behavioral characteristics of fish they produce. However, it is important to recognize that many modern hatcheries function as categorical hybrids and may conduct all three types of propagation programs in a single location. Commercial food fish and ornamental culture are beyond the scope of this chapter; however, goals of these operations are most similar to those of production hatcheries.

9.3.1 Production Hatcheries

The primary focus of production hatcheries is to produce large numbers of fish to increase recreational or commercial harvest opportunities or as mitigation to maintain fisheries affected by anthropogenic activities. These strategies attempt to increase demographic abundance, and success is typically measured in numbers of fish raised and stocked. Production hatcheries are typically medium to large facilities producing hundreds of thousands to millions of juveniles per year. Production hatcheries most commonly use industrialized rearing techniques that are focused on efficiency of juvenile fish production (see Piper et al. 1982 and Pennell and Barton 1996 for fish culture history and techniques). Fish are often reared outside in large raceways or ponds and are released in large numbers into receiving waters. Modern production hatcheries are instrumental in supplying fish to public waters. However, this industrialized approach to fish production has been criticized as contributing to the overall decline of wild populations through negative ecological interactions between hatchery and wild fish, genetic "swamping" of natural populations with inferior alleles selected for in the hatchery environment (artificial selection, inadvertent or otherwise), and fostering continued harvest of highly exploited populations (see Naish et al. 2007 for review). However, production-oriented culture methods are commonly used, particularly in support of intermittent or other put-grow-take fisheries.

9.3.2 Supplementation Hatcheries

Supplementation programs are designed to produce fish that, once reintroduced into the natural environment, will become naturally spawning wild fish. Supplementation projects generally use production hatchery rearing facilities (section 9.3.1). However, they utilize wild-caught broodstock or gametes collected from feral fish and may employ sophisticated breeding programs to ensure minimal genetic drift or artificial selection pressure (see section 9.4). Supplementation has potential benefits of reducing short-term risk of extinction, speeding recovery, recolonizing vacant habitat, and increasing harvest opportunity. Supplementation hatcheries, as opposed to production hatcheries, are a relatively recent development and one that has fueled controversy and uncertainty. The key question for supplementation programs is whether or not the contributions of wild-spawning, hatchery-origin fish are beneficial. To date, little information is available regarding the performance of supplementarily stocked fish and their progeny in the natural environment. However, the documented risks of hatchery rearing and propagation techniques (see section 9.5) should be considered prior to implementation of a supplementation program to help gauge whether supplementation will be beneficial. When supplementation is used, it should be regarded as experimental and carried out in an adaptive management framework (see section 9.6; Chapter 5).

9.3.3 Conservation Hatcheries

The goals, operational approaches, and measures of success for conservation hatcheries differ considerably from those of production or supplementation hatcheries. The mission of a modern conservation hatchery is two-fold: preservation of the gene pool and recovery of wild populations. Intensive monitoring and oversight of breeding programs are provided to ensure that sourcing, rearing, and mating protocols protect genetic integrity. Conservation hatcheries should function in ways that reflect the latest scientific information and conservation practices to maintain genetic diversity and natural behavior and to reduce the short-term risk of extinction. A conservation hatchery approach requires application and integration of a number of rearing protocols that are known to affect the inherent fitness of the fish to survive and breed in its natural environment. A conservation hatchery approach for salmonids, for example, requires a specialized rearing facility to breed and propagate a stock of fish genetically equivalent to the native stock with the full ability to return to reproduce naturally in the native habitat. A conservation hatchery must be equipped with a full complement of culture strategies to produce very specific stocks of fish with specific attributes. Fish husbandry in a conservation hatchery must be conducted in a manner that (1) mimics the natural life history patterns, (2) improves the quality and survival of hatchery-reared juveniles, and (3) lessens the genetic and behavioral influences of propagation techniques on hatchery fish and, in turn, the genetic and ecological impacts of hatchery releases on wild stocks. Operational guidelines have been described for conservation hatcheries rearing of Pacific salmon (Flagg et al. 2005; Table 9.1); however, many of the recommendations would apply to any conservation-based propagation program.

Although conservation hatchery concepts have not been in operation long enough to be

Table 9.1. Principles for hatchery management and systemwide recommendations developed by the Hatchery Scientific Review Group (modified from Mobrand et al. 2005).

Well-defined goals:

- Set goals for all stocks and manage hatchery programs on a regional scale.
- Measure success in terms of contribution to harvest, conservation, and other goals.
- Have clear goals for educational programs.

Scientific defensibility:

- Operate hatchery programs within the context of their ecosystems.
- Operate hatchery programs as either genetically integrated or segregated relative to naturally spawning populations.
- Size hatchery programs consistent with stock goals.
- Consider both freshwater and marine carrying capacity in sizing hatchery programs.
- Ensure productive habitat for hatchery programs.
- Use in-basin rearing and locally adapted broodstocks.
- Spawn adults randomly throughout the natural period of adult return.
- Use genetically benign spawning protocols that maximize effective population size and minimize potential artificial or domestication selection under hatchery conditions.
- Emphasize quality, not quantity, in fish releases.
- Reduce risks associated with outplanting (releasing hatchery fish to rear or spawn in streams).

Informed decision making:

- Adaptively manage hatchery programs.
- Incorporate flexibility into hatchery design and operation.
- Evaluate hatchery programs regularly to ensure accountability for success.

fully developed or tested, initial information indicates that rearing fish under conservation strategies may reduce aberrant behavioral and ecological interactions and increase survival (Maynard et al. 2005; Flagg et al. 2005; Hebdon et al. 2005; also see section 9.6.2). Salmon restoration in the Pacific Northwest has focused on the use of conservation hatchery strategies to aid restoration of spawning runs and rebuilding of depleted natural spawning runs (Anders 1998; Flagg and Nash 1999; Flagg et al. 2005). By means of a conservation hatchery approach, the potential for conservation and enhancement of Pacific salmon based on artificial propagation appears well grounded in other vertebrate species recovery actions worldwide (DeBlieu 1993; Olney et al. 1994; Bryant 2003).

9.4 GENETIC CONSIDERATIONS

Although there are no unambiguous, empirical studies demonstrating adverse genetic consequences of hatchery fish on wild fish populations (Campton 1995; Williamson 2001), it is still incumbent on fisheries professionals to use all practical means to limit any such effects.

9.4.1 Inbreeding

Special care must be taken in hatcheries to avoid crossing closely-related broodstock. When offspring are produced from parents sharing one or more recent ancestors they may be subject to inbreeding depression. Inbreeding depression occurs due to higher incidences of recessive (often deleterious) traits being expressed in a homozygous (identical alleles at a given locus) state. Inbred individuals may suffer from reduction in fitness due to physical abnormalities, metabolic deficiencies, or developmental anomalies (Busack and Currens 1995; Williamson 2001). Even when recessive traits are not overly prevalent among offspring, loss of fitness can occur because of an overall loss of heterozygosity. Depending on the relatedness between individuals (e.g., mating between full siblings versus half-siblings), identifiable losses of heterozygosity can happen within a few generations. Although phenotypic changes have been documented in association with the loss of heterozygosity, reductions in overall fitness are very difficult to measure because of confounding environmental effects (effects masked by ideal environmental conditions may become problematic when water quality, habitat, or prey abundance declines), imperfect correlation between measured phenotypes and absolute fitness (survival to adulthood encompasses part, but not all, of absolute fitness), and ploidy of the species (the tetraploid genome of salmonids is more resistant to loss of heterozygosity compared with the diploid genome of other fishes; Wang et al. 2002). Nonetheless, inbreeding should be avoided in propagation programs, particularly when hatchery fish are likely to interbreed with wild fish and receiving populations are at risk for loss of genetic variation.

9.4.2 Genetic drift

Whether collected recently from the wild or maintained in the hatchery for many years, hatchery broodstocks are, by definition, finite populations. Further, these populations typically represent a small subset of the wild breeding population. Small populations are more vulnerable to the actions of genetic drift, or changes in allele frequencies within a population arising from random, stochastic events rather than from selective pressures. In some respects, genetic drift can be thought of as sampling error. If only a small number of individuals are collected to establish the broodstock population, the odds are against rare alleles being represented. Assuming less-common alleles are represented in the hatchery broodstock, those alleles are vulnerable. In a small group, rare alleles are likely to be represented by a single individual; if this individual is lost, so is the allele. Genetic drift due to small effective population sizes was established as the primary explanation for divergence in allele frequencies between hatchery and wild populations of Chinook salmon (Waples and Teel 1990). As with inbreeding depression, the consequences of genetic drift may not be evident in all circumstances (i.e., populations may undergo genetic drift without an identifiable loss of fitness). Nonetheless, loss of genetic diversity can reduce the ability of populations to cope with environmental change (less "raw material" to support the process of adaptation and natural selection). Accordingly, to avoid the consequences of genetic drift in the brood and receiving populations, hatcheries should either maintain large captive populations of broodstock or consistently re-introduce new individuals from wild breeding populations.

9.4.3 Effective Population Size

To avoid inbreeding and genetic drift, hatcheries must strive to maintain an adequate number of broodstock. The field of population genetics provides a useful relationship, called effective population size (N_e), as follows:

$$N_e = 4N_mN_f / (N_m + N_f),$$

where N_m is the number of mature males and N_f is the number of mature females.

Both small numbers of spawners and unequal sex ratios will reduce the effective population size, which can be defined as the size of an ideal population of broodstock having the same rate of genetic drift as the wild population serving as the broodstock source or wild population being supplemented by the stocking. Tave (1986) recommended an N_e of 424–685 individuals. The higher number assures virtually no alleles will be lost. However, Tave recognized these numbers may not always be possible and suggested taking all steps to keep N_e as high as practical.

9.4.4 Domestication

Domestication results from the selective forces of the artificial hatchery environment or husbandry practices. From a genetics standpoint, domestication is change in the quantity, variety, or combination of alleles within a captive population or derivative broodstock in comparison with the source or donor population (Williamson 2001). Individual fish in the brood that are better suited to the hatchery setting will undergo positive selection and will survive and contribute to subsequent generations more than do their less-tolerant counterparts. The most serious form of domestication occurs when subsequent generations of captive broodfish are spawned, even when maintaining an "adequate" effective population size. Though not domestication per se, in a practical sense selection for fish with superior hatchery performance will also occur among nonbrood animals. The longer fish are held in captivity, the more they become behaviorally accustomed to their artificial surroundings and feeding protocols (see Berejikian 1995), and habituated individuals will undergo positive selection in terms of survival and growth while in the hatchery. While beneficial in the hatchery setting, acceptance of prepared feeds, reduced aversion to predators, increased aggression, and other learned behaviors are not generally advantageous in natural environments. Logistically and economically, hatcheries are limited: only so many broodfish can be maintained in a single facility; often, offspring must be held for extended periods to meet management objectives and ensure survival of the stocked fish; and, in many cases, the natural environment cannot be adequately mimicked to prevent habituation completely. Accordingly, some domestication and habituation is inevitable.

Concerns with respect to inbreeding, genetic drift, effective population sizes, and domestication are exacerbated when dealing with rare or endangered species (Rinne et al. 1986; Kohler 1995; Williamson 2001). In these specialized cases, it is crucial for hatchery personnel to take steps to preserve genetic integrity and wild-like behavior in the hatchery fish. When possible, a high N_e is vital when dealing with imperiled species, as is a conservation hatchery approach.

9.5 DISTINCTIONS BETWEEN WILD AND HATCHERY FISH

In the early days of fish culture, little thought was given to the characteristics of the fish produced, so long as they survived to be stocked into the receiving waters. However, as wild populations continued to decline despite supplementation efforts, additional consideration was given to the nature of fish produced in hatcheries. As early as the mid-1930s, researchers began questioning whether fish reared in hatcheries were somehow inferior to fish produced in the wild (Davis 1936).

Research has identified morphological, behavioral, physiological, and genetic differentiation between wild- and hatchery-reared fish. Traditional hatchery broodstock management often selected for individuals that spawned outside the normal spawning period (Flagg et al. 1995; Ford et al. 2006), resulting in early or late spawning runs among returning hatchery-origin fish. Hatchery culture practices can also alter juvenile growth and life history events such as size and age of out-migration by anadromous salmonids (Beckman et al. 1998, 1999; Larsen et al. 2001). Such life history alterations can have dramatic results, including increased male precocity and skewed temporal spawning distributions. The protective nature of hatchery rearing (i.e., reduced pressure of natural selective processes) can also increase spawned egg-to-smolt survival of hatchery-reared compared with wild salmonids (70–90% hatchery compared with only a few percent for wild; Leitritz and Lewis 1976; Piper et al. 1982; Pennell and Barton 1996). The postrelease survival and reproductive success of cultured fish are often considerably lower than that of wild-reared fish (Nickelson et al. 1986; Berejikian and Ford 2004; Naish et al. 2007), though factors unrelated to the fish themselves (e.g., stocking methods and timing of release) can also greatly influence poststocking survival (see section 9.6.3). Because of these direct or indirect changes in selective pressures, reproductive fitness of hatchery populations and fitness of their wild-spawned progeny may be reduced compared with wild populations (Berejikian and Ford 2004; Kostow 2004; Araki et al. 2007).

It is likely that the most immediate effect of traditional fish-rearing practices is disruption of innate behaviors (see section 9.6.2). In a hatchery setting, fish experience current velocities that are normally lower and more uniform than they are in nature; are not typically provided structure in which to seek refuge from predators or larger fish of the same species; are held at high, stress-inducing densities; are surface fed prepared diets; and are conditioned to approach large, moving objects at the surface (Maynard et al. 1995; Olla et al. 1998; Maynard et al. 2005). Resultant behaviors among released animals have been cited as contributing to failure in re-establishing wild populations (Johnson and Jensen 1991; DeBlieu 1993; Olney et al. 1994). Studies suggest that traditional hatchery rearing environments can profoundly influence social behavior of Pacific salmon (Maynard et al. 1995; Berejikian and Ford 2004; Naish et al. 2007). Differences in behavior may appear quite early in development, as noted by Berejikian et al. (1999), who observed greater dominance and tolerance of resource-limiting conditions among newly hatched coho salmon fry of captive-bred parentage compared with the offspring of wild fish. Social divergence of cultured fish may begin as early as the incubation stage. Lack of incubation substrate and exposure to light in the hatchery incubation environments can induce higher activity levels, resulting in reduced energetic efficiency, size, and survival (Poon 1977; Murray and Beacham 1986; Fuss and Johnson 1988). Food availability and fish rearing densities in hatcheries far exceed those found in natural streams and may contribute to differences in agonistic behavior between hatchery- and wild-reared fish (Berejikian 1995; Berejikian et al. 2001; Olla et al. 1998). Compared with wild fish, hatchery-reared brown trout have been described as inefficient foragers, expending more energy but feeding less frequently (Bachman 1984). Deverill et al. (1999) observed cultured brown trout to be similarly inefficient and thus poor growing, though most of the activity observed in these fish was associated with heightened aggressive behavior.

Reproductive success and contributions of hatchery fish to wild populations have become a double-edged sword for culturists and managers (see Box 9.1). Numerous studies have demonstrated reduced reproductive success of hatchery fish due to intentional or unintentional selection for spawning time (Chilcote et al. 1986). In these situations, hatcheries are rebuked for not producing fish that contribute maximally to subsequent generations in the wild. Conversely, hatcheries have also been admonished for producing fish that dominate wild gene pools either through behavioral dominance or simply by numbers. Fish culturists need to incorporate techniques to minimize the differences between hatchery and wild fish and to help mitigate the effects of artificial rearing and any negative influences of hatchery fish once stocked (see section 9.6.2).

9.6 BEST MANAGEMENT PRACTICES FOR PROPAGATION AND STOCKING PROGRAMS

9.6.1 Selection of Propagation and Stocking Strategies to Achieve Management Objectives

Hatchery conditions and operational procedures must reflect potential differences between wild and hatchery fish and whether these differences (see section 9.5) will pose considerable risk to the wild population. A key factor in determining the type of stocking or management option a hatchery will undertake is the biological significance of the stock. Biological significance is a function of the stock's origin, inherent genetic diversity, biological attributes and uniqueness, local adaptation, and genetic structure relative to other conspecific populations. McElhany et al. (2000) described four key population parameters that can be used to assess

Box 9.1. Hatcheries and the Endangered Species Act

From the 1950s to the 1960s, natural resource industries (i.e., timber and capture fisheries) were key components of the Pacific Northwest economy. This period also heralded the industrial phase of Pacific salmon hatchery operation to cope with increasing harvest pressures, regional development (e.g., expansion of transportation systems, construction of impoundments, and clearing of forested watersheds) and the attendant loss of freshwater habitat. Production peaked in the 1980s, with more than 420 million fry, fingerlings, and smolts released annually along the west coast of North America (Mahnken et al. 1998).

The 1980s and early 1990s saw an increased understanding of impacts of natural resource exploitation in the Pacific Northwest (e.g., the spotted owl issue and the effects of hatcheries on wild coho salmon populations in the Columbia River [Flagg et al. 1995]). In addition, Pacific Northwest economies were growing, diversifying, and shifting away from natural resource exploitation. A major change in salmon management philosophy occurred in the early 1990s with the listing of Columbia River salmon populations under the U.S. Endangered Species Act (ESA). The ESA is the cornerstone of U.S. legislation to prevent the loss of biodiversity and includes among its provisions a prohibition against harassing, harming, killing, capturing, or collecting a listed species (defined by the statute as a “take”; 16 U.S.C. §1538[a]) and the requirement that all federal agencies ensure their actions are “not likely to jeopardize the continued existence of any [listed species] or result in the destruction or adverse modification of habitat of such species” (16 U.S.C. §1536[a][2]). In 2007, 27 stocks of anadromous salmon and steelhead on the Pacific coast (states of Washington, Idaho, Oregon, and California) were listed by the National Oceanic and Atmospheric Administration National Marine Fisheries Service as threatened or endangered under the ESA. Unlike other listed species, Pacific salmonids are unique in that they co-exist with large hatchery-supplied, ocean-ranching populations. Current hatchery practices and harvest methods have been considered contributing factors leading to the overall decline of wild populations (Waples 1991; Lichatowich 1999; Levin et al. 2001), and thus the traditional, production-oriented strategies of fish propagation have come into conflict with the mandates of the ESA. The need to preserve wild fish biodiversity and meet the demands of the ESA has led biologists, managers, and culturists to rethink propagation of Pacific salmon and steelhead on the west coast of the USA.

Where hatchery operations conflict with recovery of ESA-listed stocks, the options appear to be (1) manage hatchery production as a reproductively distinct population (i.e., genetically segregated from naturally spawning populations) or (2) manage hatchery production as a genetically integrated component of a natural population by means of conservation-oriented approaches (see section 9.3.3; Flagg and Nash 1999; Flagg et al. 2005; Mobrand et al. 2005 for details of conservation hatchery operation). Mobrand et al. (2005) described two genetic management options to complement integrated versus segregated strategies, and each leads to a different set of operational guidelines (detailed information on integrated versus segregated approaches can be found on the Hatchery Scientific Review Group [HSRG] Website: www.hatcheryreform.us).

(Box continues)

Box 9.1. Continued.

In a segregated hatchery program, the goal is to produce a distinct hatchery-supported population that is reproductively isolated from wild populations (HSRG 2004a). A segregated program creates a new, hatchery-adapted population intended to meet goals for harvest or other purposes (e.g., research and education) while allowing for imperiled stocks to recover. In a segregated program, broodstocks are sourced from returning hatchery fish and, thus, little to no gene flow occurs between natural-origin spawners (NOS) and hatchery-origin spawners (HOS). Over time, a genetically distinct, hatchery-adapted population develops because of founder effects, genetic drift, and domestication selection in the hatchery environment (Mobrand et al. 2005). To prevent undesired transfer of hatchery-adapted characteristics to wild populations, the HSRG (2004a) recommends the percent of HOS should be less than 5% of the number of NOS on the spawning grounds. The degree to which segregated hatchery programs are successful depends significantly on the degree to which genetic and ecological risks to natural populations can be minimized. A critical aspect of this strategy is complete, or near complete, harvest of returning HOS to prevent genetic or other interactions with NOS.

In an integrated hatchery program, the goal is to minimize the genetic effects of domestication by allowing selection pressures in the natural environment to drive the genetic constitution and mean fitness of wild- and hatchery-origin fish (HSRG 2004b). The intent of an integrated program is to increase the abundance of a natural population demographically while at the same time minimizing the genetic effects of hatchery propagation. Genetically integrated broodstocks must include a prescribed proportion of wild fish in the broodstock each year to maintain genetic integration with a natural population (Mobrand et al. 2005). For any fixed proportion of NOS incorporated into the hatchery broodstock (pNOB), the smaller the proportion of HOS on the spawning grounds (pHOS), the stronger the opportunity for the natural environment to drive adaptation (HSRG 2004b). Thus, the HSRG (2004b) recommends the pNOB exceed the pHOS for an integrated program and that the pNOB should be a minimum of 10% to avoid divergence of the hatchery population from the natural component, even when pHOS is 0. Further, for stocks of moderate or high biological significance and viability (or to maintain or improve the current biological significance and viability of the stock), the HSRG (2004b) recommends the "realized spawning composition" (pNOB / [pHOS + pNOB]) be greater than 0.7. A successful integration program thus requires sufficient returns of NOS to supplement the broodstock each year and natural habitat capable of sustaining this natural population. Therefore, the size of composite populations generated by integrated programs will be limited by habitat availability and the ability to restrict natural spawning by hatchery-origin adults.

Implementation of either a genetically segregated or a genetically integrated strategy requires the ability to distinguish hatchery- and natural-origin adults, both in the hatchery and on the natural spawning grounds, to assess the genetic risks and gene flow rates. Both strategies require that a majority (or preferably all) of the fish carry discernable distinguishing

(Box continues)

Box 9.1. Continued.

marks (e.g., tags or fin clips). Both types of programs require methods to remove hatchery-origin fish prior to reaching spawning grounds to control hatchery-to-wild fish ratios adequately on the spawning grounds. Often, achievement of these goals will require a combination of directed selective fisheries and control structures such as weirs to remove adequate numbers of fish prior to arrival on spawning grounds.

the viability and biological importance of salmon populations: (1) abundance, (2) growth rate, (3) spatial structure, and (4) diversity. The viability and biological importance of the supplemented population will determine, in part, the propagation strategy—more sensitive or unique wild populations will demand more conservative propagation strategies.

Several generalized guides have been published regarding the use of propagation for stocks of Pacific salmon, including those at high risk of extinction (Hard et al. 1992; Flagg and Nash 1999; Flagg et al. 2005). However, these guides are designed to be broadly applicable and do not offer specific recommendations to ensure success of the stocking program. Essentially, the guides suggest the stocking and management strategy should depend on the particular stock of fish, its level of depletion, the physical and management limitations of each individual hatchery action, and the biodiversity of the ecosystem. Reviewing the characteristics of the target population, receiving ecosystem, and available propagation strategies is critically important to tailoring the guidelines to achieve specific management objectives. We focus on the particulars of propagation and stocking strategies in the following sections. However, effective use of hatcheries and cultured fishes must also include an assessment of the relative risks and benefits of management and supplementation strategies.

In light of possible effects of stocked fish, either introduced or supplemental, on wild populations and the high cost of producing fish for stocking, not stocking should always be considered as an option. For example, in cases where habitat restoration would also elicit the desired outcome, directing resources to habitat improvements instead of stocking efforts may ultimately be more cost-effective and ecologically sustainable. Increasing diversity may not always be achievable because the stocked species may flourish at the expense of existing species already popular with the fishing public. Genetic alterations of populations being supplemented with hatchery fish can also be problematic. In light of these and other considerations, risk assessment approaches may be useful in determining the most economically- and ecologically-appropriate course of action. Risk assessments assist decision makers by assessing a proposed activity in terms of the probability and consequences of a negative outcome. Risk assessments also attempt to describe, if not measure, uncertainty associated with the activity and its effects. Applied to stocking programs, risk assessments can be used to summarize genetic and other interactions between hatchery and wild fish, effects on other species in the ecosystem, and the uncertainty associated with ecological responses to stocking (Pearsons and Hopley 1999). While these assessments can be very useful in terms of describing risk, whether the level of risk is acceptable is a separate question that should be addressed by means of the best available science, professional experience, and the opinion of stakeholders and the general public. If the decision to use propagated fish is made, the following guidelines may be used to improve culture and stocking methods.

9.6.2 Husbandry Techniques and Hatchery Operation

Mobrand et al. (2005) described three foundational principles for best management practices for operation of hatcheries (Table 9.2).

Principle 1—Every hatchery stock must have well-defined goals in terms of desired benefits and purpose. Well-defined goals for operation of hatcheries provide both explicit targets and measures for success. Stocking goals must reflect the purpose and desired benefits of the program (e.g., harvest, conservation, research, or education). An integrated hatchery program should include short-term and long-term goals for production and outcomes, as well as monitoring plans in place to track progress. Hatcheries should delineate specific objectives to meet these goals. Goals and objectives should be explicit and include (1) the intended number of fish to be harvested each year, (2) the number of fish returning to a hatchery or spawning naturally in a watershed (i.e., escapement), (3) the expected results of any associated scientific research, and (4) the benefits to be derived from education and outreach components.

Principle 2—Hatchery programs must be scientifically defensible. The stated goals of stocking programs and the day-to-day operations of hatcheries must be scientifically defensible. They must represent a logical approach to achieve the management goals and should be based on knowledge of the target ecosystem and the best scientific information available. Once the goals for a program are established, the scientific rationale for the design and operation of the program must be explicitly described so that the scientific basis of operation and day-to-day activities may be understood by all personnel and, ideally, the general public. In line with principle 1, a written, comprehensive management plan for every hatchery program, covering broodstock management, fish rearing, and release and harvest management components, is imperative to program acceptance and successful implementation. These guidelines should include a decision-making procedure to use in developing the initial project goals and a course of action to achieve these goals. The decision-making guide can also be very useful in justifying hatchery operation or dealing with contingencies after the plan has been implemented. Further, scientific oversight and peer review should be integral components of every hatchery program.

Principle 3—Hatchery programs must respond adaptively to new information. Scientific monitoring and evaluation of the hatchery and stocked fish are necessary to ensure that hatcheries are achieving their goals. Evaluation should include assessment of juvenile-to-adult survival and, where applicable, returns to spawning grounds; contributions of hatchery-origin adults to harvest and natural reproduction; and rates of hatchery fish migration or straying to nontarget waters. Where possible, evaluation should include assessments of genetic and ecological interactions (e.g., interbreeding, competition, and predation) between hatchery- and natural-origin fish. Results should be evaluated annually to allow timely programmatic adjustments, and hatcheries should always be managed adaptively to respond to new goals, new scientific information, and changes in the status of natural stocks and habitat.

To summarize these principles, there is a need for increased monitoring and evaluation, scientific oversight, and accountability of hatchery operations. Hatcheries need to operate in scientifically defensible modes with well-defined goals and substantially increased data collection and evaluation. Hatcheries also need to be flexible and adaptable; that is, they need to operate and be evaluated in the context of both the ecosystem in which the hatcheries occur and the ecological processes on which hatchery-origin fish depend. Scientific uncertainties associated with hatchery operations are numerous. The science to manage these risks is still inadequate and some of the risks are poorly understood (see Currens and Busack 2005). It

Table 9.2. Operational comparisons between production and conservation hatchery strategies for rearing of Pacific salmon (modified from Flagg et al. 2005).

Parameter and factor	Production hatchery		Conservation hatchery	
	Action	Objective	Action	Objective
Egg collection				
Spawn timing	Directed (e.g., early or late component)	Synchronize adult return or harvest opportunities	Synchronized to wild; representative numbers collected over range of run	Maintain wild timing
Number	Directed (probably large number of eggs taken)	Maximize output	Directed (relatively small number of eggs needed)	Stage production to habitat carrying capacity
Egg fertilization				
Mating strategy	Directed (for characteristics)	Selected desired attributes (e.g., (return size and age)	Directed (to maintain genetic diversity	Maintain diversity
Egg incubation				
Incubator type	Use accepted guidelines for species	Maximize output	Include substrate	Approximate wild conditions and maximize hatch size
Temperature	Surface or well	Time hatch to production needs	Controlled to ambient for stock	Synchronize hatch with wild timing

Table 9.2. Continued.

Parameter and factor	Production hatchery		Conservation hatchery	
	Action	Objective	Action	Objective
Fish rearing				
Vessel type	Standard (typically smooth with no internal structure)	Maximize output	Altered to include enriched (seminatural) habitats with cover, structure, substrate, or other	Reduce domestic conditioning
Temperature	Surface or well	Time rearing to production needs	Controlled to ambient for stock	Synchronize rearing with wild stock
Culture techniques	Standard (designed to maximize fish output)	Maximize output	Innovative (designed to maximize fish quality)	Reduce domestic conditioning and improve fitness
Pond timing	Variable	Maximize culture opportunity	Synchronized to wild	Approximate wild rearing scenario
Photoperiod	Natural	Provide ambient conditions	Natural	Provide ambient conditions
Density	Up to maximum safe levels	Maximize space use	Use low rearing density	Minimize behavioral and health concerns

is clear that maintaining healthy habitat is critical not only for viable, self-sustaining natural populations but also to control risks of hatchery programs adequately and realize the benefits of hatcheries to recover populations and sustain healthy harvests in increasingly populated environments (Mobrand et al. 2005). Hatcheries cannot be regarded as surrogates or substitutes for lost habitat, declining environmental quality, or adequate regulation and management of capture fisheries; rather, hatcheries should be viewed as a complementary component of broader natural resource management and restoration activities (see Box 9.2).

In a recent review, Brown and Day (2002) highlighted the similarities between the goals of fisheries management and conservation biology.

Lessons from conservation biology. Although conservation biologists may be concerned with preserving the unique attributes of populations, whereas managers may be more interested in maintaining commercial or recreational fisheries, in either case the aim is to establish (or re-establish) self-sustaining populations. For hatchery fish to contribute to this common goal, at a minimum, they must survive long enough to reach a harvestable size and sexual maturity. Brown and Day (2002) outlined a series of changes in rearing methods that might enhance postrelease success of hatchery fish. Although these suggestions are from the conservation biology perspective and may be most applicable or feasible in a conservation hatchery setting, it is important to recognize that any hatchery or stocking program would benefit from enhanced postrelease survival.

Brown and Day (2002) acknowledge the importance of broodstock selection and maintenance in order to avoid problems such as inbreeding and domestication (see section 9.4) but focus on morphological differences and learned behaviors (see section 9.5) as the primary contributors to postrelease mortality of hatchery fish. To some extent, morphological alterations (e.g., coloration, fin morphology, growth rate and size, and tissue composition) can be corrected by providing natural or seminatural foods, reducing production densities, or using seminatural lighting (Maynard et al. 1995). However, use of natural or seminatural rearing environments appears to result in the most comprehensive restoration of wild morphology and behavior. The authors noted several behaviors that are critical to the success of stocked fishes: predator recognition and avoidance, recognition and acquisition of food, appropriate social interactions with conspecifics, identification or construction of needed habitats (e.g., nests), and navigation and locomotion in complex environments. Exposure to some level of structural complexity prior to stocking (seminatural streambeds, submerged structure, overhead cover, or use of earthen ponds instead of tanks or raceways), particularly in conjunction with the opportunity for natural or seminatural foraging, appears to provide some sort of behavioral "life skills training" and increase postsurvival stocking of hatchery fishes (Brown and Day 2002). Although these techniques are certainly more labor- and resource-intensive than are traditional propagation protocols, if greater poststocking survival is achieved, they may be more cost-effective in the long term.

9.6.3 Stocking Techniques

9.6.3.1 Transportation of fish

Regardless of where fish originate, some amount of travel must occur to transport fish to the receiving system. Most agencies possess fish hauling vehicles that consist of vehicle-mounted tanks and some type of aeration device (e.g., agitators, blowers, or pressurized

Box 9.2. Hatchery Fish and Restoration of Striped Bass in the Chesapeake Bay

Historically, striped bass populations along the U.S. Atlantic coast supported lucrative and popular commercial and recreational fisheries. Annual harvests peaked in 1973 at 6,700 metric tons but rapidly declined over the next 10 years under the pressures of zealous harvest, habitat modification, and reduced water quality (Richards and Rago 1999). By 1983, the striped bass catch had dwindled to approximately 15% of peak harvest. In response, the Atlantic States Marine Fisheries Commission developed an Interstate Fisheries Management Plan for the striped bass and these recommendations were later vested with regulatory authority by the 1984 Atlantic Striped Bass Conservation Act (Public Law 98–613). Recognizing striped bass recruitment on the Atlantic coast is largely supported by the Chesapeake Bay spawning and nursery grounds, biologists targeted the bay for intensive restoration efforts. Although striped bass had been stocked along the coast since the late 1800s (Rulifson and Laney 1999), intensive stocking of the Chesapeake Bay began in earnest in 1985. By 1993, 7.5 million fingerling striped bass had been released into the bay (Richards and Rago 1999). Given the strong influence of temporal and stochastic effects on larval striped bass survival, fry were also released into the Chesapeake Bay system to compensate for high mortality among natural spawns (Secor and Houde 1998).

The Chesapeake Bay striped bass fishery was declared recovered in 1995 and today all migratory stocks of the Atlantic striped bass are considered restored to historic levels (Rulifson and Laney 1999). Some have argued the rebound of striped bass in eastern U.S. waters is due largely to restricted harvest pressure and stocking efforts contributed little to the restoration of Chesapeake Bay striped bass (Richards and Rago 1999). However, hatchery-origin fish are represented in the growing subadult and reproductively-mature year-classes, particularly in the Patuxent River (Rulifson and Laney 1999). Reduced fishing pressure combined with habitat improvement certainly enhances the likelihood of wild- and hatchery-origin fish contributing to natural recruitment.

It has been suggested that hatchery supplementation alone cannot restore overexploited populations (Lorenzen 2008). Rather, successful fishery enhancements are generally characterized by a “major transformation of the fisheries system,” including propagation and release of cultured fish, implementation of more restrictive harvest limits, increased population monitoring and regulatory oversight, and greater involvement of stakeholders to speed acceptance and compliance with new regulation (Lorenzen 2008). In the case of the Chesapeake Bay striped bass, it is unlikely that stocking alone would have resulted in an equally rapid and robust resurrection. However, recovery of the Atlantic striped bass populations is an excellent example of how hatchery fish can be implemented as part of a multifaceted approach to fishery restoration and enhancement.

cylinders of gaseous or liquid oxygen). Proper care during transport is critical to the success of a stocking program because of the high potential for stress-induced mortality due to handling, crowding, disease exposure, osmotic shock, or temperature shock (see Carmichael et al. 2001). Feed is typically withheld for 24–48 h prior to transport to reduce subsequent egestion-related fouling in the hauling tank. Fish may be given a prophylactic treatment with an antibiotic or other therapeutant prior to or during transport; although prophylactic treatment may reduce the incidence of disease, it is not routinely used because of withdrawal times (typically 7–21 d) required for many approved drugs. In the event drugs are used, whether in the hatchery or during transport, only approved products should be applied in strict accordance with guidelines for their use in aquaculture (up-to-date information on drugs approved for use in U.S. aquaculture can be obtained from the U.S. Fish and Wildlife Service Aquatic Animal Drug Approval Partnership Program, www.fws.gov/fisheries/aadap/home.htm).

Hauling tanks may be disinfected with calcium hypochlorite and rinsed thoroughly prior to filling with culture water. When necessary, the water can be cooled to desirable hauling temperatures (15–20°C for cool- and warmwater fishes; 10–15°C for coldwater fishes), but care must be taken to acclimate the fish slowly to the new temperature. A good rule of thumb is to temper fish for 30 min for each 1°C change in excess of a 2°C difference in temperature. Assuming other differences in water chemistry between hatchery and receiving waters are minor, acclimation is generally unnecessary if the temperature difference (cooler or warmer) is less than 2°C. Hauling waters should be supersaturated with oxygen at the outset and regulated to maintain dissolved oxygen content in excess of 5 mg/L for the entire haul. Depending on species, salt (NaCl) is often added to hauling water to attain a salinity level of 3–7 ‰ to assist fish in maintaining their osmotic balance. Water changes are sometimes necessary during long hauls; all the preceding precautionary steps should be taken when exchanging water during a haul. Loading rates by weight will vary depending upon distance to the stocking site, species of fish, size (smaller fish = smaller loading weight), temperature, water hardness (lower levels of divalent cations = lower loading rates), and aeration efficiency. An example of loads and distances are shown in Table 9.3.

It is critical to ensure transport and stocking activities do not inadvertently contribute to the spread of aquatic animal diseases or invasive species. This includes compliance with recommended procedures to prevent transfer of aquatic nuisance species (e.g., removal of organisms and debris from vehicles and vessels and disinfection of equipment prior to traveling to another location) and transportation restrictions or prohibitions (e.g., federal restrictions on

Table 9.3. Pounds of catfish that can be transported per gallon of 18.3°C (65°F) water (from Piper et al. 1982).

Number of fish per pound	Transit period in hours		
	8	12	16
1	6.30	5.55	4.80
2	5.90	4.80	3.45
4	5.00	4.10	2.95
50	3.45	2.50	2.05
125	2.95	2.20	1.80
250	2.20	1.75	1.50
500	1.75	1.65	1.25
1,000	1.25	1.00	0.70
10,000	0.20	0.20	0.20

interstate transport of susceptible species to control the spread of viral hemorrhagic septicemia in the Great Lakes region).

9.6.3.2 Choice of taxa stocked

Considering all the rationales for stocking, it should come as no surprise that numerous taxa, encompassing nearly all trophic levels and biological characteristics, have been stocked in North America (Heidinger 1999). In 2004, government agencies stocked 104 taxa (species, subspecies, or hybrids) in U.S. waters (Halverson 2008). Of the 1.75×10^9 individual fish stocked in 2004, a majority (82%) were stocked for sportfishing or as forage to benefit sport fisheries. Stockings of imperiled or rare species were minor in terms of numbers and biomass stocked; however, these species represent roughly half of the species propagated in 2004. Increasing production of ESA-listed or otherwise at-risk fishes reflects the growing importance of "conservation aquaculture" and imperiled species restoration in aquatic ecosystem management (see section 9.8). Table 9.4 provides some generalized information on representative species and pertinent characteristics that influence decisions to stock.

9.6.3.3 Sizes and numbers stocked

Depending on the species and stocking goal, fish can be stocked as fry (larvae), fingerlings, advanced fingerlings, or adults (herein, catchables). Large numbers of fry might be stocked with the assumption that some will survive, or, alternatively, a smaller number of larger fish might be stocked. In general, larger fish will have greater survival rates because they are more tolerant of stressors associated with transport and stocking (Pitman and Gutreuter 1993) and are less vulnerable to predation. However, larger fish are more difficult and costly to produce. Decisions to rear and stock fish at various life stages and sizes may be based on biology, ease of culture, management goals, economics, politics, or any combination thereof (Hartman and Preston 2001). For example, walleye are routinely stocked at smaller sizes because of issues associated with rearing large numbers of advanced fingerlings in captivity (i.e., difficulty of feed training, cannibalism, and economics). In 2004, walleye represented nearly 60% of the total number of fish stocked by state and federal agencies in the USA but less than 1% of the total biomass stocked (Halverson 2008). Conversely, species such as rainbow trout are highly tolerant of culture procedures and are often stocked at catchable sizes. Rainbow trout represented about 5% of the number of fish stocked in the USA in 2004 but approximately 50% of the biomass (Halverson 2008). Stocking catchable-size fish, such as for a put-and-take trout fishery, can result in an instant public relations boon because of the speed at which the hatchery-produced fish find their way to the fisher's creel. It is not uncommon for greater than 90% of hatchery trout to be caught within weeks of a put-and-take stocking (see section 9.6.3.4). Urban fishing programs also rely on stockings of catchable-size fish, with catfishes, sunfishes, and common carp being quite popular.

The decision on size and number to stock is often based on what is most practical as opposed to a detailed cost-effectiveness analysis. However, cost-effectiveness analyses can be very helpful in determining the most efficient means (releasing fry, fingerlings, or catchables) of meeting a management goal (e.g., increased recruitment or greater returns to the creel; Leber et al. 2005) and may be increasingly used by natural resource agencies facing budget cuts. Ideally, stocking rates should also account for density-dependent effects on survival—while low stocking rates may not achieve the desired outcome, very high stocking rates may also result in poor

Table 9.4. List of selected taxa that are stocked and some of the pertinent biological characteristics to consider when choosing a fish for stocking (modified from Heidinger 1999).

Taxon	Characteristics
Atherinidae	
Inland silverside	Forage fish; winterkills but can tolerate colder temperatures than can threadfin shad; young of the year reproduce in Midwest
Centrarchidae	
Black crappie	Easier to handle and transport than is white crappie; tends to predominate over white crappie in northern and southern portions of USA; does not readily accept a prepared diet
Bluegill	Becomes stunted in small ponds and can limit largemouth bass recruitment; readily accepts prepared diets
Green sunfish	Very vulnerable to largemouth bass predation
Hybrid sunfishes	Grows faster than parental species; certain F_1s are predominately males; F_1s tend to be fertile
Largemouth bass	Sport fish; Florida largemouth bass cannot survive in cold water as well as can northern largemouth bass
Redear sunfish	Harder to catch than are bluegill; capable of eating mollusks; does not readily accept a prepared diet
Smallmouth bass	Grows well on insects and crayfishes as forage; grows well at warm temperatures but does not recruit in southern states in ponds with largemouth bass and sunfishes present; in the southern part of its range it recruits in streams
White crappie	Tends to overpopulate in small ponds and lakes or does not recruit; tends to dominate over black crappie in turbid water; does not readily accept a prepared diet
Clupeidae	
Gizzard shad	Very fecund forage species; not desired in small pond or lake if managing for sunfishes; spawns at 2 years
Threadfin shad	Very fecund forage species; young of the year spawn; winterkills at temperatures below 8°C
Cyprinidae	
Common carp	Commercial species; capable of eating infauna; highly fecund; long lived; wide temperature tolerance
Fathead minnow	Forage fish; so vulnerable that species tends to be eliminated by largemouth bass
Golden shiner	Has been stocked in small lakes and ponds as forage for largemouth bass; tends to be more successful in northern part of largemouth bass range; in Midwest may overpopulate and limit largemouth bass recruitment
Grass carp	Used as biological control of vegetation; stocked at 5 to 15 fish per hectare; triploids are available; not approved in all states; commonly reaches 14 kg; very vulnerable to largemouth bass predation below 20 cm

Table 9.4. Continued.

Taxon	Characteristics
Esocidae	
Muskellunge	Trophy sport fish; fry are very vulnerable to fish predation
Tiger muskellunge	Accepted as trophy sport fish by most muskellunge anglers; easier to raise to advanced fingerling stage on prepared diet than are parental species; sterile
Ictaluridae	
Black and yellow bullheads	Used in urban fisheries; tend to reproduce at small size (15 cm); dense populations capable of keeping a pond muddy in areas of colloidal clay
Channel catfish	Requires cavity in which to spawn; very vulnerable to largemouth bass predation below 15–20 cm; may not recruit in small ponds; will readily accept prepared diets
Moronidae	
Hybrid striped bass	Cross using female striped bass and male white bass (palmetto bass) grows larger than reciprocal (sunshine bass); easier to train to take prepared diet than parental species; will backcross
Striped bass	Pelagic sport fish capable of eating large forage fish not vulnerable to other piscivores; floating eggs require large headwater stream to recruit; some populations are maintained by stocking fry

survival and recruitment due to increased intraspecific competition for resources (Fayram et al. 2005). The presence of predators, abundance of prey, and carrying capacity of the receiving system should all be considered when determining stocking rates and size at release.

9.6.3.4 Timing and stocking site

Most of the North American fish fauna spawn in spring, so fry will be stocked at that time, fingerlings in late spring to early summer, and advanced fingerlings in fall. It is advantageous to time fry and small fingerling stockings to peaks in zooplankton populations, but in practice this occurs more serendipitously than as a result of planning (Heidinger 1999; Hartman and Preston 2001). As temperatures rise, so does the risk of stress and disease outbreaks after stocking, so, excluding northern regions, fish are not routinely stocked in summertime. Winter also presents a set of problems in that fish handled at cold temperatures (particularly warmwater and coolwater species) are more prone to fungal infection. Ice coverage of receiving systems can also be a deterrent to stocking in winter.

Larval fish can be harmed when subjected to bright sunlight, therefore, evening or early morning stocking is recommended. Fish species or life stages that are pelagic in nature should be stocked in open waters as opposed to near a convenient boat-launching ramp. Care should also be taken to stock littoral species or life stages along shorelines containing structural habitat such as aquatic vegetation or woody debris. In the case of anadromous fishes, juvenile releases normally occur at acclimation sites to encourage returns to target watersheds. In all cases, prior to releasing fish, water quality should be measured at prospective stocking sites to avoid unsuitable areas (e.g., low dissolved oxygen) and to determine the amount of acclimation needed to compensate for differences in water chemistry between the hauling and receiving waters (Pitman and Gutreuter 1993).

Risk of immediate postrelease mortality can also be minimized by stocking at multiple locations in a receiving water body and spreading stocking efforts over a period of days or weeks. Stocking at different times and locations minimizes the risk of complete failure but is not routinely done because of the need for additional personnel and other logistical problems associated with multiple releases. Similarly, so-called "soft releases" can improve postrelease survival but are often impractical. Whereas a "hard release" will involve little more than tempering prior to stocking, a soft release includes an extended acclimation period prior to release and, in some cases, may involve release into a protected confinement (i.e., a cage or net pen) prior to full release (Brown and Day 2002). Although routine in reintroduction of terrestrial species, soft releases are relatively uncommon in fisheries enhancement and restoration.

Put-and-take stockings are different than those described above in that the management goal is often to maximize return to the angler's creel. Accordingly, fish are often stocked in open view at locations easily accessible to the hauling vehicle and the fishing public. Upcoming stocking events might also be covered by local media, drawing even more anglers to the stocking site. This process often results in "truck following," whereby anglers are casting lines even before the truck pulls away.

9.6.3.5 Evaluation of stocking programs

A critical part of any management plan involving a stocking program should include an assessment of its successes, failures, or unintended consequences (Murphy and Kelso 1986; Wahl et al. 1995). Management plans should clearly state the rationale(s) for the stocking and the intended outcome(s). An introduction stocking can readily be assessed by sampling for the presence of offspring from stocked fish and, ultimately, their progeny if a self-sustaining population develops. Likewise, supplemental stockings can be evaluated on the extent they strengthen a given year-class, but some sort of marking program (genetics, chemical markers, or tags; see Guy et al. 1996) is necessary to confirm the relative contributions of stocked and wild fish. Creel surveys are a simple and effective method to evaluate whether a stocking has improved fishing from a quantity aspect. On the other hand, creating a trophy fishery via stocking can improve the quality of the fishing experience, but more detailed interviews of the fishing public are necessary to gather this sort of information (see Knuth and McMullin 1996). Unintended consequences of stockings (e.g., genetic pollution, interspecific competition, or habitat disruption) are more difficult to evaluate in that they are often not readily apparent or do not occur for many years. Unless stocking has previously been undertaken over an extended period, a management plan should include a research component to evaluate ecological considerations in addition to the more immediate impact on the fishing public.

9.7 CRITICISMS OF FISH CULTURE AND HATCHERY FISH

Many fisheries professionals and lay people share an outdated view of fish culture and its use in fisheries management and restoration. Many inaccurately equate fish culture with juggernaut factory farms and dismiss the role of hatcheries in fisheries management because of an assumed “quantity-not-quality” driven approach. For example, Helfman (2007) stated,

> Aquaculture as currently practiced may create additional pressure on wild stocks because of competition for (1) larvae and other fishes that are fed to cultured stocks, (2) coastal ecosystems and their services, and (3) world markets where products are sold. Also, capture fisheries and marine ecosystems will likely suffer due to problems of waste production, chemical pollution, exotic species invasions, and pathogen transmission. Supplementation programs, therefore, have an effect opposite of their purported goals, reducing wild fish abundance when wild fish can least afford additional insults and populations are at historic lows. Hatchery activities and population supplementation cannot be justified on the grounds of conserving wild populations, now or in the future.

Helfman (2007) concluded, “Hatcheries accelerate extinction.” This indictment of fish culture is not supported by scientific information and does not reflect the opinion of most fisheries professionals. The vast majority of fisheries managers have concluded that fish culture is integral to fisheries conservation and restoration, and management strategies cannot be divorced from the culture practices upon which they rely. It is correct that fish culture alone will not compensate for the effects of overharvest, habitat degradation, or other stressors; however, many fisheries exist only because of the efforts of fish culturists. Globally, stock enhancement and culture-based fisheries activities yield approximately 20% of freshwater and diadromous capture fisheries (Lorenzen et al. 2001). In the Pacific Northwest, it is estimated that 70–80% of some coastal fisheries are based on hatchery releases (Mahnken et al. 1998; Naish et al. 2007). Further, the availability of commercially-cultured seafood reduces harvest pressure on wild populations. Arguments to the contrary are fueled largely by cultural and socioeconomic ties to traditional capture fisheries.

With respect to hatchery and stocking programs, it is important to recognize that traditional hatchery operating procedures were not established with modern goals of supplementation or restoration in mind. Hatcheries have and continue to operate at the behest of public interest. When stocking rates were the sole measure of success, hatchery managers concerned themselves with production volumes. As maintenance of genetic diversity and the role of local adaptation became prominent paradigms, hatchery managers changed their focus from numbers to genotypic and phenotypic characteristics—modern hatcheries aim for quantity and quality, a central theme of American Fisheries Society symposia addressing the use of propagated fishes (Stroud 1986; Schramm and Piper 1995; Nickum et al. 2005) and a topic increasingly emphasized during revision of this chapter for this volume (see Kohler and Hubert 1993, 1999). Scientific uncertainty and unanticipated effects of hatchery rearing and stocking may have limited the positive impacts of hatcheries in the past. However, the negative consequences of traditional stock enhancement are now being used in an adaptive management strategy to inform the process of hatchery reform.

Some exotic species introductions can be tied to accidental releases from aquaculture facilities, but a large number of introductions blamed on fish culturists were purposeful stockings conducted under the direction of natural resource agency initiatives (Mitchell and Kelly 2006). While some introductions and stocking programs have had unexpected, negative consequences (e.g., habitat degradation and competition with native species), fish culture and stocking cannot be dismissed as a management tool because some strategies have proven ill advised. It is a popular assumption that all nonnative species are overwhelmingly destructive, and most reports have focused on cases for which negative consequences have been observed (Gozlan 2008). In fact, many introductions have had positive economic effects and have enhanced biodiversity without negative ecological impacts. In a review of the economic and ecological costs of nonnative species, Pimentel et al. (2005) generally lamented the negative effects of exotic fishes on endemic populations in the USA but also conceded that introductions of nonnative fishes have yielded considerable economic benefits in the form of sport fishery enhancement. Further, in some instances exotic species (e.g., grass carp and western mosquitofish) have proven tremendously useful as biological controls for enhancing environmental quality and restoring ecological function. For the majority of freshwater species that have been introduced to systems outside their native distribution, the risk of negative ecological impact following introduction is only 10% (Gozlan 2008). Of course, the relative ecological risk varies among species and can be minimized by implementing additional preventative measures to avoid accidental introductions of higher-risk species. For further discussion of the positive and negative impacts of introduced fishes, we refer the reader to Chapter 8.

Pathogen transmission from culture facilities to wild populations is a hotly-debated issue that continues to be fueled by conflicting data. Because of the nature of fish and their pathogens, it is essentially impossible to prevent pathogen transfer during movement of fish from one locale to another. When transferred to “naïve” fish populations by relocation or introduction, introduced pathogens can become problematic. In addition to the usual concerns associated with exotic species introduction, transfer of nonindigenous cultured fish can be a vector for disease or infestation of wild populations, as evidenced by transfer-related outbreaks of whirling disease among rainbow trout in the Pacific Northwest and sea lice infestations of Atlantic salmon in Norway (Waples 1999). However, when propagation and stocking efforts are restricted to regionally-sourced, indigenous species, pathogen transfer between hatcheries and wild fish is less likely. In any event, cases of pathogen transmission from hatcheries to wild populations are largely unsubstantiated in the USA and current measures to control pathogen releases appear to be effective (LaPatra 2003).

Many of the other criticisms leveled at fish culture can be traced to public perception of commercial operations, particularly those rearing marine, carnivorous fishes. Aspects of culturing these species remain contentious, but the long-term success of the industry relies upon increasing sustainability and reducing impacts. The question of competition for larvae, that is, capturing wild-spawned larvae for grow-out in captivity, is largely restricted to commercial culture of marine food fishes, such as tunas, because spawning or larval husbandry techniques are as yet lacking for these species. Use of “trash” fishes as food for large carnivorous animals is primarily restricted to commercial operations, where it is dwindling as suitable formulated feeds are being developed.

Fish feeds are also controversial, owing to the use of reduction fishery products, that is, fish meals (FM) and oils (FO), in their formulation. Concern regarding FM- and FO-based feeds is a widespread issue, affecting both private and public fish culture operations. Driven by concerns of feed cost, product availability, and, more recently, transfer of persistent organic contaminants, the Food and Agriculture Organization of the United Nations (FAO) has described the development of animal feeds free of FM and FO as “a major international research priority” (FAO 2005). Many argue against the transformation of small pelagic fishes into FM and FO, contending these fishes could be directly consumed by humans (Naylor et al. 2000). In the Asian-Pacific region, most of the “trash fishery” landings are consumed directly by humans; only 25% of landings are incorporated into aquaculture feeds (FAO 2005). However, most Western consumers are unwilling to accept these trash fish as foods, and landings of wild food-grade fishes are simply insufficient to keep pace with demand (FAO 2009). Strides have been made in reducing or eliminating reduction fishery products in aquafeeds (New and Wijkström 2002). In the case of salmon feeds, FM inclusion rates have decreased from 60% in 1985 to a current average of approximately 35% (Tacon 2005). Modern grow-out feeds formulated for herbivorous or omnivorous species typically contain 2–15% FM, whereas feeds for carnivorous species contain 20–50% FM (Tacon 2005). Nutritionists continue to refine formulations and have been increasingly successful at partially or completely replacing FM and FO without affecting production performance (reviews by Hardy and Tacon 2002; Sargent et al. 2002; Trushenski et al. 2006; Gatlin et al. 2007). Formulations are also continually modified to enhance digestibility and nutrient retention, which reduces production cost and waste production (Cho and Bureau 2001). In time, these experimental formulations will be adopted by commercial feed manufacturers and, in turn, fish culture operations.

9.8 THE FUTURE OF FISH CULTURE AS A MANAGEMENT TOOL

The effective use of cultured fishes and stocking as a management tool is guided by science but is also subject to political, social, and economic forces. The decision whether to use cultured fishes is complex, and it is impossible to gauge the future of fish propagation and stocking programs with certainty. By examining recent trends in the use of cultured fishes, however, we can gain some insight into the ways in which fish culture and stocking practices might evolve. To assess current stocking practices in terms of the historic record, Halverson (2008) reviewed stocking activities conducted by U.S. federal and state agencies from 1931 to 2004. The review revealed a number of trends that we can reasonably expect to continue into the future: (1) decreasing involvement of federal agencies in stocking programs; (2) larger individuals and greater total biomass being stocked; and (3) greater diversity of taxa being stocked, particularly rare or imperiled fishes.

Decreasing federal involvement in fish stocking programs reflects a broader trend in natural resource management, specifically decentralization and the transfer of federal responsibilities to states or communities. The transfer of responsibility to regional or local governments has been touted as a means to provide greater flexibility and efficiency and greater incentives for program execution, compliance, and success because the regulatory power is put in the hands of the stakeholders (Andersson et al. 2004). Many federal hatcheries in the USA and Canada have been transferred to the states or provinces, and a majority of those that remain federally operated have transitioned to propagation of native or imperiled species used in restoration or mitigation programs (Edwards and Nickum 1993; Jackson et al. 2005). In terms of individuals produced, federal contributions to fish stocked in U.S. waters have declined from roughly 70% in the 1930s to less than 8% in 2004 (a conservative estimate based on the 33 states for which data were available; Halverson 2008). In turn, state agencies are increasingly involved in fish culture and stocking efforts: nationwide, approximately one-third of full-time state fisheries personnel are involved in fish production and distribution (Gabelhouse 2005) and one- third of state fisheries expenditures are for the purposes of hatchery and stocking programs (Ross and Loomis 1999).

Historically, propagation and stocking techniques involved little more than seeding systems with fertilized eggs. As the limitations of these strategies became evident, culturists increasingly focused on production of larger individuals that would have a greater likelihood of survival in the wild. In the 1940s, large fish (>15.2 cm) represented roughly 20% of all fish stocked in U.S. waters; in recent years, the contribution of large individuals has grown to more than 50%. Although production of advanced fingerlings and catchables required greater inputs, it was assumed these costs would be outweighed by the benefits accrued to the target population and fishing public. Stocking of larger individuals has proven successful in terms of increasing creel returns and continues to be the standardized approach for many species. During this same period, inland commercial fisheries were becoming less relevant to the U.S. food supply and economy, and management priorities were shifting from commercial fisheries enhancement to sport fisheries and recreational fishing opportunities. In many cases, this transition meant rigorous efforts to expand the range of sport fishes, often with little expectation of establishing self-sustaining populations (see section 9.2). Current stocking efforts are dominated by sport fishes, by number (72% of total) and by biomass (82% of total). Given the demands of the sportfishing public, recreational fisheries enhancement is unlikely to wane considerably in the near future. However, widespread recognition of the importance of ecosystems instead of individual species has placed a premium on ecosystem-based approaches to aquatic resource management. Fisheries agencies in the USA and Canada have begun to view stocking in the context of broader management strategies, and management plans are less likely to rely solely on propagated fishes (Jackson et al. 2005). Stocking programs will be increasingly paired with habitat rehabilitation, pollutant and stressor mitigation, harvest restrictions, and other methods in a more holistic approach to restoring aquatic ecosystems and inland fisheries. Further, as philosophical and statutory imperatives to protect imperiled species become more prominent among fisheries professionals and the lay public, propagation of threatened and endangered fishes will grow.

9.9 CONCLUSIONS

The use of propagated fishes in inland fisheries management has a long, though controversial, history in North America. Early efforts were hampered by incomplete knowledge of husbandry and stocking techniques; later efforts became limited by their own success, as the differences between hatchery and wild fishes and the impacts of stocking became evident. Nonetheless, the usefulness of stocking and the importance of cultured fishes to achieving management programs cannot be denied. Hatchery reform, adoption of risk management and decision-making tools, and increased emphasis on conservation aquaculture and ecosystem-based approaches will ensure the continued relevance of cultured fishes to adaptive management of aquatic resources.

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