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Marine Fisheries Enhancement: Coming of Age in the New Millennium

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Article Outline

Glossary

Anadromous Species that spawn in freshwater, then their offspring gradually make their way into estuaries or the sea, where they remain during much of the subadult and adult stages of the life cycle, before returning to rivers and streams to spawn.

Catadromous Species whose females release their eggs at sea, then the offspring move as larvae or early juveniles into estuaries, rivers, and streams where they spend the juvenile stage of the life cycle.

Marine Species that spawn in sea water, including those that spend most of their lives at sea and catadromous fishes, which spawn in seawater, then enter freshwater nursery habitats.

Marine fisheries enhancement Release of aquacultured marine organisms into seas and estuaries to increase or restore abundance and fishery yields in the wild.

Outbreeding depression Caused when offspring from crosses between individuals from different populations or subpopulations (stocks) have lower fitness than progeny from crosses between individuals from the same population/stock.

Recruitment The process of joining an existing population. Species *recruit* to the juvenile stages in nursery habitats; juveniles subsequently *recruit* to adult stages in adult habitats. Species *recruit* to a fishery when they reach the minimum size fished.

Reintroduction Temporary release of cultured organisms with the aim of reestablishing a locally extinct population.

Restocking Release of cultured juveniles into wild population(s) to restore severely depleted spawning biomass to a level where it can once again provide regular, substantial yields.

Sea ranching Release of cultured juveniles into unenclosed marine and estuarine environments for harvest at a larger size in "put, grow, and take" operations.

Stock enhancement The release of cultured juveniles into wild populations to augment the natural supply of juveniles and optimize harvests by overcoming limitations in juvenile recruitment.

Supplementation Moderate release of cultured fish into very small and declining populations, with the aim of reducing extinction risk and conserving genetic diversity. Supplementation serves primarily conservation aims and specifically addresses sustainability issues and genetic threats in small and declining populations.

Definition of the Subject

Marine fisheries enhancement (aka "stock enhancement") is the use of hatchery-reared saltwater

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organisms to increase abundance and fishery yields in the wild. "Conservation hatcheries" also produce and stock depleted, threatened, or endangered organisms – to help preserve species in decline. The practice began in the latter part of the nineteenth century when fish hatcheries were first developed but understanding of the ecology and management of wild stocks into which the hatchery-reared organisms where released was very limited. Early stock enhancement thus has gone through a series of fits and starts and misfires. In the century after its birth, the technologies required for scientific inquiry of the effects and effectiveness of stocking hatchery-reared organisms were lacking. The science needed to guide reliable use of cultured aquatic organisms in conservation and resource management remained undeveloped. Then, at the close of the twentieth century, new mariculture, tagging, and genetic technologies surfaced and rapid advances were made in the science underpinning marine stock enhancement.

As growth in human population size approaches the carrying capacity of the planet in this century, and the world increasingly turns to the oceans to farm and harvest food [1], sustainable fishery yields and conservation of natural resources face unparalleled challenges. Over the past two decades, marine fisheries enhancement has been transformed from a tentative, poorly developed management tool to a maturing science. Some believe research funding for this field would be better spent on traditional fishery management. But today's seafood producers, fishery managers, and "…conservationists need all the tools that biology, ecology, diplomacy and politics can muster if endangered species are to survive beyond the next century," and [2] fisheries are to continue to support a viable seafood industry and sport pastime. This entry traces the emergence and progress of marine fisheries enhancement, and offers a prescription for future direction.

The term *stock enhancement* is originally derived from efforts to augment wild fish sub-populations, or "stocks," by releasing cultured fishes into aquatic environments. Stocking cultured organisms is one of the tools available for managing aquatic natural resources. It has been used with varying degrees of success to help increase abundance of habitat- or recruitment-limited stocks to help restore depleted populations, augment fisheries and help recover threatened or endangered species. There has been much debate over the effectiveness of stock enhancement as a fisheries management tool. However, most of the scientific evaluation of stocking is quite recent [3], as is a code of responsible practices that help guide effective application [4–6], and marine fisheries enhancement is finally poised for effective use.

In the USA, from the 1880s through the early 1950s, stocking hatchery-reared marine fishes was a principal approach used by the US Fish Commission (renamed Bureau of Fisheries in 1903, Bureau of Commercial fisheries in 1956, and later the National Marine Fisheries Service) for maintaining fishery stocks. But by the 1950s the practice of stocking marine fishes to manage US fisheries was curtailed for lack of evidence of its effectiveness in fisheries management [7]. Stocking was replaced by harvest management to control total catch and sustain fisheries. Stocking of freshwater habitats continued (particularly with salmonids into rivers), although the scientific basis for many of the management decisions needed for stocking salmonids was clearly lacking and did not begin to be addressed until the mid-1970s.

In the decade following 1975, scientists began to evaluate survival and fishery contributions of stocked salmon enabled by advances in fish tagging technology [8, 9]. Quantitative evaluation of marine fish stocking began in earnest in the 1980s and 1990s. The science underlying fisheries enhancement has since evolved to the point where, in some situations, stocking can be a useful fishery management tool to help restore depleted stocks and increase abundance in recruitment-limited fisheries [6]. Effective use of enhancement, though, requires full integration with harvest and habitat management, and a good understanding by stakeholders and resource managers of the opportunities where enhancement can be used successfully as well as its limitations [5, 6]. Principles for guiding the successful use of marine fisheries enhancement to help sustain aquatic resources are now being employed to design new enhancements and reform existing efforts. What follows is a brief overview of those principles and progress made in using hatchery-reared organisms to help sustain marine resources.

Introduction

Marine fisheries enhancement is happening around the world and in some countries on a massive scale (e.g., China). However, in many countries the careful assessment of genetic and ecological risks is lagging behind implementation, putting wild stocks, the seafood supply, and sport fisheries at risk. The science of marine enhancement is still in its infancy compared to other fields of fisheries science, but now shows potential to (1) increase fishery yield beyond that achievable by exploitation of the wild stock alone, (2) help restore depleted stocks, (3) provide protection for endangered species, and (4) provide critical information on the natural ecology, life history and environmental requirements of valuable marine species.

Stock enhancement has often been used as a generic term referring to all forms of hatchery-based fisheries enhancement. Bell et al. [3] and Lorenzen et al. [6] classified the intent of stocking cultured organisms in aquatic ecosystems into various basic objectives. Together, they considered five basic types, listed here from the most production-oriented to the most conservation-oriented:

1. Sea ranching – *recurring release of cultured juveniles into unenclosed marine and estuarine environments for harvest at a larger size in "put, grow, and take" operations.* The intent here is to maximize production for commercial or recreational fisheries. Note that the released animals are not expected to contribute to spawning biomass, although this can occur when harvest size exceeds size at first maturity or when not all the released animals are harvested.
2. Stock enhancement – *recurring release of cultured juveniles into wild population(s) to augment the natural supply of juveniles and optimize harvests by overcoming recruitment limitation in the face of intensive exploitation and/or habitat degradation.* Stock enhancements can increase abundance and fisheries yield, supporting greater total catch than could be sustained by the wild stock alone [10]. However, such increases may be offset, at least in part, by negative ecological, genetic, or harvesting impacts on the wild stock component. Stock enhancements tend to attract greater numbers of fishers, which can offset expected increase in each individual's catch-per-unit-effort (CPUE) [5, 11].
3. Restocking – *time-limited release of cultured juveniles into wild population(s) to restore severely depleted spawning biomass to a level where it can once again provide regular, substantial yields* [12]. Restocking requires release number to be substantial relative to the abundance of the remaining wild stock, and close ecological and genetic integration of wild and cultured stocks, combined with very restricted harvesting [6].
4. Supplementation – *moderate releases of cultured fish into very small and declining populations, with the aim of reducing extinction risk and conserving genetic diversity* [13, 14]. Supplementation serves primarily conservation aims and specifically addresses sustainability issues and genetic threats in small and declining populations [6].
5. Reintroduction – *involves temporary releases with the aim of reestablishing a locally extinct population* [15]. Continued releases should not occur, as they could interfere with natural selection in the newly established population. Fishing should also be restricted to allow the population to increase in abundance rapidly [6].

Scientific development of marine fisheries enhancement was lacking throughout most of the twentieth century. Although stocking cultured marine fishes began in the nineteenth century, the technology was limited to stocking only eggs and larvae. There were no published accounts of the fate of released fish until empirical studies of anadromous salmonids began to be published in the mid-1970s [16, 17], followed by the first studies (published in English) of stocked marine invertebrates in 1983 [18, 19] and marine fishes in 1989 [20].

During the past two decades, the field of marine fisheries enhancement has advanced considerably. Science in this field is rapidly growing, in part because of critical examination and debate about the efficacy of enhancement and the need for quantitative evaluation (e.g., [21, 22]), and in part because of advances made in aquaculture, genetics, tagging, and fishery modeling technologies, which have enabled quantitative studies and predictions of stocking effects. A clear process has emerged for developing, evaluating, and using enhancement [4–6]. Together, this process and the rapid growth of knowledge about enhancement effects should enable responsible and effective use of enhancement in marine fisheries management and ocean conservation.

Scientific Development of Marine Fisheries Enhancement

Scientific and Strategic Development

Since 1989, progress in marine fisheries enhancement has occurred at two levels – scientific advances and adoption of a careful and responsible approach to planning and organizing enhancement programs and manipulating abundance of marine species using aquacultured stocks. Much of the progress made in the 1990s was scientific and involved an expansion of field studies to evaluate survival of released fish and improve the effectiveness of release strategies. The earliest studies (found by the author) on effectiveness of stocking *marine* fishes, published in English in the scientific literature, were in Japan [20, 23–26] and Norway [27–31], followed by studies in the USA [32–39], and Australia [40]. Progress made with invertebrates is well covered by Bell et al. [12].

Following the initial publications of scientific studies of marine fish enhancement, the number of peer-reviewed publications and symposia in this field began to escalate ([41–52], and see abstracts in [53]). It is now clear that stocking marine organisms can be an effective addition to fishery management strategies, but only when certain conditions are met. For stocking to be productive and economical, and help ensure sustainability of wild stocks, careful attention must be given to several key factors and stocking must be thoroughly integrated with fisheries management [6]. It is clear that stocking can be harmful to wild stocks if not used carefully and responsibly.

Aside from scientific gains in this field, the other level of progress made in the past two decades has been the evolution of a strategic "blueprint" for enhancements, such as the principles discussed in "a responsible approach to marine stock enhancement" [4, 6]. By the early 1990s, salmon enhancement in the US Pacific Northwest, which had been underway for a century, was beginning to incorporate reforms that were needed to improve efficiencies and protect wild stocks from genetic hazards that can lead to loss of genetic diversity and fitness. Concerns had been mounting over uncertainty about the actual effectiveness of salmon hatcheries and impacts on wild stocks. Concerns about wild stocks were twofold, including ecological effects of hatchery fish, such as competitive displacement, and genetic issues, such as translocation of salmon stocks, domestication and inbreeding in the hatchery and associated outbreeding depression, and loss of genetic diversity related to hatchery breeding practices (e.g., [54, 55]). Meanwhile, special sessions on marine stock enhancement began appearing at major fisheries and mariculture conferences in the early 1990s [41–44]. These sessions took a sharp turn from past approaches, where the principal focus in conference presentations about stock enhancement had been mainly on Mariculture research topics alone. The conveners of the special sessions on stock enhancement in the 1990s recruited presenters who worked on evaluating the effects and effectiveness of stocking hatchery organisms into the sea and interactions of hatchery and wild stocks. The special sessions focused on the "questions of the day" in marine enhancement and fostered debate in the marine enhancement research community about many of the reform issues being considered in salmon enhancement. The early 1990s was a period of rapid developments in enhancements, characterized by engagement of multiple scientific disciplines in a field that had previously been guided largely by a single discipline – aquaculture.

The salmon experience and reforms under way in salmon enhancement made it clear that a careful and multidisciplinary approach was needed in the development and use of marine enhancement. Many involved in developing new marine fisheries enhancement projects were paying close attention to the debate that had emerged over salmon hatcheries. Following the 1993 special session on "fisheries and aquaculture interactions" held at a mariculture conference in Torremolinos, Spain [44], several of the presenters (including scientists from Japan, Norway, the USA, and Italy [United Nations Food and Agriculture Organization, FAO]) met and formed an "International Working Group on Stock Enhancement," and affiliated the workgroup with the World Aquaculture Society. At that inaugural working group meeting, a decision was made to publish a platform paper to

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frame the question, "what is a responsible approach to marine stock enhancement?" This paper was presented at the 1994 American Fisheries Society symposium, "Uses and Effects of Cultured Fishes in Aquatic Ecosystems," and published in the 1995 peer-reviewed symposium proceedings [4]. The paper recommended ten principles for developing, evaluating, and managing marine stock enhancement programs. The Responsible Approach paper afforded a model for developing and managing new enhancement programs and refining existing ones. It has also helped frame research questions in the emerging science of marine fisheries enhancement.

The International Working Group on Stock Enhancement (IWGSE) was instrumental in advancing the science of marine fisheries enhancement in the 1990s. The working group focused primarily on highlighting ongoing stock enhancement research around the world and fostering awareness of the Responsible Approach in their publications and presentations. International awareness and new research in the field was aided by the broad international makeup of the working group. Membership grew and soon included scientists from Australia, Canada, China, Denmark, Ecuador, Italy, Japan, Norway, Philippines, Solomon Islands, Spain, the UK, and the USA. Initially, the primary vehicle used by the working group was the special sessions on stock enhancement, which it planned and convened annually in various countries at the international conference of the World Aquaculture Society. The working group promoted a synergy among its members and the influence of the group expanded as members planned additional workshops and symposiums in their own countries and brought IWGSE scientists into the planning process.

The period 1990–1997 was a fertile time that gave birth to a rapid expansion of science in marine fisheries enhancement, which continues to this day, aided since 1997 in large part by the International Symposium on Stock Enhancement and Sea Ranching (ISSESR). The first ISSESR, held in 1997 in Bergen, Norway, was the brainchild of the Norwegian PUSH program (Program for Development and Encouragement of Sea Ranching) and the Norwegian Institute of Marine Research (IMR). In 1995, IMR scientists invited IWGSE scientists to become involved in the International Scientific Committee charged with planning the program for the first ISSESR. The first ISSESR, and the series of follow-up symposia that it launched (see www.SeaRanching.org), have encouraged and brought about fundamental advancements in the field of marine enhancement – by networking the scientists working in this specialized field, highlighting their work at the ISSESR, and publishing their peer-reviewed articles in the symposium proceedings. The 3–5 day ISSESR has now become a regular scientific symposium event, hosted by a different country every 4–5 years. Following the first ISSESR in Bergen [47], subsequent symposiums in the series were held in Kobe, Japan in 2002 [49], in Seattle, USA in 2006 [52], and in Shanghai, China in 2011 [53]. The fifth ISSESR will be held in Sydney, Australia in 2015 or 2016. Inquiries from scientists in different countries interested in hosting the sixth one are already being received by the organizing group. Following the first ISSESR, the IWGSE scientists continued the efforts they started in the working group through their involvement in the International Scientific Committees for the ISSESR and steering committees for other stock enhancement symposia (e.g., [46, 48, 51]). In 2010, a refined and updated version of the Responsible Approach was published [6] and presented at the fourth ISSESR.

As in any new science, lack of a paradigm and consensus on the key issues retard progress. The ISSESR and other marine enhancement symposia and working groups have helped to place scientific focus on critical uncertainties and communicate results of new science in this field at symposiums and in the scientific literature. They have also provided a forum for debate on the issues, and increased networking of scientists, resource managers, students, and educators working in this field worldwide. The focus on key issues is nurturing this new field of science.

Technological and Tactical Constraints

Although marine enhancements do show promise as an important tool in fisheries management, why has this field taken so long to develop and why have marine enhancement programs often failed to achieve their objectives? The scientific development of marine fisheries enhancement has long been impeded by lack of the technologies needed to evaluate effects of stocking cultured fish. Although marine enhancements began in the 1880s, until the advent of the coded-wire tag in the mid-1960s [8], there was no way to identify treatment groups and replicates in experimental releases of juvenile cultured fish [56]; and quantitative marking methods for multiple experimental groups of postlarvae and very small juveniles (<50 mm in length) came much later (e.g., [57]). To make matters worse, scientific development of marine enhancement was also stymied by lack of adequate technology for culturing marine fishes. Rearing methods for larval and juvenile marine fishes, many of which require live feeds during the larval stage, remained undeveloped until the mid- to late 1970s, when breakthroughs finally began to be achieved in rearing a few marine species past metamorphosis [58]. By the mid-1980s mass production of juveniles had been achieved for several species of marine fishes. Even today, though, many marine fishes cannot yet be cultivated to the juvenile stage in the quantities needed for stocking. Without the availability of juveniles grown to a wide range of sizes, fundamental questions about density dependence, hatchery-wild fish interactions and cost-yield efficiency of size-at-release and other release variables cannot be addressed in field experiments. Thus, even the basic technologies needed to develop and understand the potential of marine enhancement have been unavailable until relatively recent times for some fishes and have yet to be developed for others.

Technology has not been the only constraint to successful development of marine fisheries enhancement. The effective use of stocking cultured marine organisms in fisheries management has been hindered by lack of understanding of the effect of releases on fish population dynamics and a lack of related, quantitative assessment tools [10]. Moreover, there has been a lack of essential governance and fisheries management considerations in planning, designing, implementing, and evaluating enhancement programs [6, 59]. A symptom of this is the relentless concern among stakeholders and hatchery managers alike about the numerical magnitude of fish released, rather than on the effective contribution of the hatchery program to fisheries management goals. Certainly, a hatchery needs to meet some release quotas, but the numbers of fish released is a misleading statistic for gauging success or comparing effectiveness among enhancement programs. Yet, from the very beginning, progress has been judged by the number of eggs, yolk-sac larvae or juveniles stocked, rather than by the number of fish added to the catch or to spawning stock biomass. The thinking behind this approach apparently is "grow and release lots of hatchery fish and of course they'll survive and add to the catch," without realizing the need to optimize release strategies (e.g., [39, 60, 61]) (e.g., to know what size-at-release and release magnitude combination has the greatest impact on population size, fishery yields, and economics), or that the impact from stocking could in fact be a negative one on wild stocks (such as replacement of wild fish by hatchery fish) if certain precautions are not taken. This attitude has been pervasive and exists even today among many stakeholders and enhancement administrators. In fact, research now shows that survival and recruitment to the fishery following hatchery releases is a complex issue that requires much greater understanding about the fishery, hatchery fish performance, and biological and ecological factors in the wild than simply "the catch is down, thus releasing large numbers of fish will bring it back up." And quite often large release magnitudes are achieved by releasing millions of postlarvae, rather than fewer but larger juveniles. Yet releases of postlarvae alone may be effective, but can also be totally ineffective, depending on conditions at the release site [62].

The key to successful use of stocking is to plan enhancement programs from a fisheries/resource management perspective, using a broad framework and scientific approach [6, 59]. The probability of achieving effective results is greatly increased when stakeholders are engaged from the outset in planning *new* programs, using a framework that is structured, multilayered, participatory, and makes good use of science, to design, implement, and analyze enhancement fisheries systems [6]. Incorporating the key principles in the Responsible Approach into the frameworks of *existing* programs as well is likely to improve performance.

Responsible Approach to Marine Fishery Enhancement

In retrospect, the slow development of marine fish culture (a century behind salmonid aquaculture) has helped marine stock enhancement programs avoid some of the mistakes of the past made with salmon stock enhancement, where lack of understanding of genetic issues during most of the twentieth century led to inadvertent domestication and inbreeding in salmon hatchery populations, leading to reduced fitness in wild stocks. Marine finfish juvenile production technology lagged behind freshwater and anadromous fish culture by a century. Thus, mass release into the sea of juvenile marine fishes large enough to survive and enter the breeding population did not begin until the 1980s. The relatively recent capabilities to conduct marine fisheries enhancement emerged at about the same time that geneticists realized that hatchery practices with salmonids (1) could reduce genetic diversity in the hatchery and ultimately, enhanced wild stocks, owing to inadequate broodstock management, (2) have caused translocations of salmon genes into environments where they are less fit, and (3) have contributed to loss of local adaptations in the wild population. Today, population genetics is much better understood and broodstock genetics and hatchery practices can be better managed to reduce these concerns (e.g., [63–65]). Thus, marine enhancement programs need careful guidance from qualified geneticists. The Puget Sound and Coastal Washington Hatchery Reform Project in the USA has been instrumental in reforming salmon enhancements [66]. This group affords a model for managing enhancement hatcheries in the twenty-first century.

As progress was being made in the early 1990s to better understand the genetic structure of stocks and how to manage genetics in hatcheries, realizing the need for reform in approaches to enhancing non-salmonids was just beginning. In the mid-1990s, Cowx [67], for enhancements in freshwater systems, and Blankenship and Leber [4], for enhancements in marine and estuarine systems, published papers calling for a broader, more systematic, reliable, and accountable approach to planning stock enhancement programs. Prompted both by the salmonid hatchery reform movement and by the WAS IWGSE, the ten principles presented in Blankenship and Leber ([4] Table 1) gained widespread acceptance as the "Responsible Approach" to stocking marine organisms and provided a platform for subsequent discussions on planning, conducting, and evaluating marine enhancements (e.g., [6, 12, 22, 51, 52, 68–70]). Since 1995, the awareness of the Responsible Approach has steadily increased and has helped guide hatchery and reform processes for marine enhancements worldwide [11, 36, 37, 39, 60, 62, 69–90].

The Responsible Approach provides a conceptual framework and logical strategy for using aquaculture technology to help conserve and increase natural resources. The approach prescribes several key components as integral parts of developing, evaluating and managing marine fisheries enhancement programs. Each principle is considered essential to manage enhancements in a sustainable fashion and optimize the results obtained [4, 6].

A major development since the publication of the original "Responsible Approach" has been increasing interest from fisheries ecologists in understanding and quantifying the effects of hatchery releases from a fisheries management perspective. This has led to the development of fisheries assessment models that can be used to evaluate stocking as a management option alongside fishing regulations [5, 10]. At the same time, approaches to fisheries governance underwent major changes that allow enhancements to become more integrated into the management framework and in some cases, were driven by interest in enhancement approaches [59].

Walters and Martell [5] discuss four main ways that a marine enhancement program can end up causing more harm than good: (1) the replacement of wild with hatchery recruits, with no net increase in the total stock available for harvest (competition/predation effects); (2) unregulated fishing-effort responses to the presence of hatchery fish that cause overfishing of the wild stock; (3) "overexploitation" of the forage resource base for the stocked species, with attendant ecosystem-scale impacts; and (4) genetic impacts on the long-term viability of the wild stock. They stress that it is critical to monitor the impacts of enhancement as the program develops to have evidence in hand if debate about the efficacy of the program does surface. To help guide developing programs, they provide and discuss a "Code of Responsible Conduct" as critical steps in marine fisheries enhancement program design (Table 2).

In 2010, Lorenzen, Leber, and Blankenship [6] published an updated version of the Responsible Approach to refine the original key principles and include five additional ones (Table 3). The key

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principles added in the updated version bring stakeholders more firmly into the planning process;place much stronger emphasis on a-priori evaluation of the potential impact of enhancements using quantitative models; place marine fishery enhancements more firmly within the context of fishery management systems; emphasize design of appropriate aquaculture rearing systems and practices; and incorporate institutional arrangements for managing enhancements. Lorenzen et al. [6] provide comprehensive discussions for each of the 15 key principles listed in Table 3. Readers are urged to consult Lorenzen et al. [6] for additional detail, as it is beyond the scope, here, to repeat their discussions of each principle.

The 15 principles in the updated Responsible Approach include the broad range of issues that need to be addressed if enhancements are to be developed or reformed responsibly [6]. Clearly, marine enhancement programs are multidisciplinary and their effective use requires specialist knowledge and skills from diverse fields (Table 4). Forming interdisciplinary teams of the various specialists required is an important factor in employing the Responsible Approach in developing, reforming, and executing marine enhancements. For effective design of enhancement programs, specialists in each area of expertise listed in Table 4 should be included in the planning teams.

It should be clear that without a careful monitoring system in place, marine enhancements simply cannot be managed. Monitoring is essential to understand the impacts of enhancement, to manage release strategies so that they are efficient and designed well enough to achieve the goals of the program, to protect against misuse of stocking (as discussed in 5 and 6), resulting in harm to wild stocks, and to document success or failure in meeting enhancement program objectives. Walters and Martel [5] list several key monitoring requirements for managing fishery enhancements well: (1) mark all (or at least a high and known proportion of) fish released from hatcheries; (2) mark as many wild juveniles as possible at the same sizes/locations as hatchery fish are being released; (3) experimentally vary hatchery releases over a wide range from year to year and from area to area, probably in on/off alternation (temporal blocking) so as to break up the confounding of competition/predation effects with shared environmental effects; (4) monitor changes in total recruitment to, production of, and fishing effort in impacted fisheries, not just the percentage contribution of hatchery fish to production; (5) monitor changes in the fishing mortality rates of both wild and hatchery fish directly, through carefully conducted tagging programs that measure short-term probabilities of capture; and (6) monitor reproductive performance of hatchery-origin fish and hatchery-wild hybrid crosses in the wild. Sound management-action design and monitoring is the essence of adaptive management [91] and adaptive management enables refinements, progress, and success in marine enhancement programs [4, 6, 11, 92].

Marine fisheries enhancement is a powerful tool that requires careful and interdisciplinary planning to control its effects. The process of transforming marine enhancement from an idea before its time into an effective resource management and sea ranching tool involves adopting a clear prescription for responsible use. As marine enhancement comes of age in this new millennium, agencies and stakeholders have a growing library of protocols for enhancement at their disposal and the responsibility to use them. The Responsible Approach and Code of Responsible Conduct provide healthy prescriptions for controlling the outcome of enhancements. These principles need to be adopted and used well, in order to increase and ensure the readiness of this tool to aid in conservation and to increase fishery yields when it is needed. Growth in human population size is fast approaching a critical level, and much greater attention will be placed in this century on obtaining food from the sea [1]. It is not possible to not to be ready with marine enhancement to help sustain depleted, threatened, and endangered species, help maintain wild stocks in the face of increasing fishing pressure, help sustain sports fisheries, and help increase fishery yields.

Legacy from the Past

Allure of a Quick Fix

Marine enhancement programs are often seen as a "quick fix" for a wide variety of problems in marine resource management. At best, they may be an important new component of marine ecosystem management; if not implemented responsibly, though, they may lull fishery managers into false confidence and thus lead to inaction and delay in the development of other fisheries management and restoration programs [5, 6].

Although marine fisheries enhancement is certainly not a quick fix, it can be a powerful tool for resource management when conditions warrant the use of this tool and if the time and care needed are taken to develop enhancement programs well. Unfortunately, the allure of a quick fix has often prompted stakeholders and managers to skip or ignore several elements needed to allow those programs to succeed, leading to wholesale failure of such efforts. The field of marine fisheries enhancement is littered with examples of enhancement projects that failed to achieve their potential for lack of a careful enough or quantitative approach (e.g., see accounts discussed in [7, 21, 62, 72, 93–95]). Most of the failures can be traced back to attempts to use enhancements when they were not warranted or failure to consider several, if not most, of the principles now incorporated in the "Responsible Approach" and "Code of Responsible Conduct" for marine fisheries enhancement.

Isolation from the Fisheries Science Community

Historically, marine fisheries enhancements have been conducted more or less isolated from other forms of fisheries management. Enhancement hatcheries have often been promoted by stakeholders and government mandates without the necessary funding or authorization behind them to do much more than produce and release fish without funds for monitoring impacts and adaptive management needed to increase the effectiveness of enhancements. Such programs are often built and implemented from a vantage point within resource management agencies that has little or no connectivity with the existing fishery management process. This has stymied development of this field in two ways – first, by compelling hatcheries to operate within resource management agencies largely independent from stock assessment and fisheries monitoring programs, or even worse, within different agencies altogether. Second, such isolation has fostered development of a production-oriented operational mode, and thwarted development of an enhancement-oriented mode [92].

Part of this isolation from fishery management also stems from the poor track record of the early marine hatcheries as an effective way to recover depleted fish stocks, coupled with the lack of scientific development of marine fisheries enhancement for so long into the twentieth century. This has understandably led to bias against fishery enhancements. Many of today's fishery scientists have been schooled to understand that stock enhancement has not worked, based in part on the lingering legacy from past failures and in part on lack of awareness of new marine fisheries enhancement science, as few citations have yet appeared in fisheries science textbooks. With many of the scientific achievements in fisheries enhancement having occurred only over the past decade or so, this is understandable. But in light of the need to couple fisheries enhancement with fisheries management systems, lack of awareness of progress in this field is an obstacle that may be resolved only by compilation of more and more success stories over time. Thus, it is imperative that existing and developing enhancement programs alike incorporate modern concepts about how to plan and conduct enhancements so they are enabled for success.

Progress in Marine Fisheries Enhancement

Lessons Learned from Marine Enhancement Programs

Much progress has now been made in understanding how to manage enhancement more effectively. Bartley and Bell [96] considered progress made from three decades of stocking initiatives and summarized and discussed lessons learned. These are listed here, below [96], with a brief clarification or caveat on each.

Deciding When and How to Apply the Release of Cultured Juveniles

1. Objective assessment of the need for releases is crucial –and requires an evaluation of the status of the fishery, modeling of stocking impact to determine if stocking can help achieve the goals, coupled with consideration of whether there are recruitment limitations and adequate habitat available for stocking.
2. Releases of cultured juveniles for restocking and stock enhancement need to be made at the scale of self-replenishing populations –releases will not be effective unless the spatial extent of target populations has been identified; thus prior to

conducting releases of hatchery organisms, clear identification of genetically discrete stocks should be determined.

3. There are no generic methods for restocking and stock enhancement –largely because of wide variation in life history among different species and variation in ecological conditions among release sites.
4. Very large numbers of juveniles are often needed for effective stock enhancement –this is particularly so for offshore stocks, which can be comprised of a huge number of individuals; more modest releases may suffice for localized enhancement of inshore stocks or those comprised of multiple stocks that occur on relatively small scales.
5. Large areas are needed for stock enhancement of some species –and this can result in user conflict, particularly for sea ranching, where large areas are leased and protected by the enhancement program (e.g., [97]); in other cases, limited dispersal of adults and larvae indicates stocking in smaller areas can be effective, for example, common snook along Florida's Gulf Coast [98].
6. Invertebrates offer good opportunities for restocking and stock enhancement –because invertebrates are often comprised of self-recruiting populations that occur at small scales.

Integrating Interventions with Other Management Measures

7. Problems that caused lower production must be addressed before release of juveniles – particularly in the case of degraded, lost, or insufficient habitat.
8. Biotechnical research must be integrated with institutional and socio-economic issues – ownership rights and control and use of enhanced stocks need to be well understood by the greater institutional, social, economic, and political environment [99].
9. Successful stock enhancement programs are often run by cooperatives and the private sector – where there is increased incentive in sharing the costs of fisheries enhancement.
10. The costs and time frames involved in restocking programs can be prohibitive – hatchery costs, which can be considerable, are particularly difficult to bear in smaller countries and developing countries.

Monitoring and Evaluation

11. Development of cost-effective tagging methods is critical to efficient evaluation of stock enhancement – refining and monitoring the effects and effectiveness of marine enhancements cannot be done without a way to distinguish hatchery from wild stocks and distinct release groups.
12. Large-scale releases of hatchery-reared juveniles can affect genetic [fitness] of wild populations – genetic hazards can be caused by hatchery-wild fish interactions and these need to be minimized.

Reducing the Cost of Juveniles

13. Costs of stocking programs can be reduced by "piggybacking" production of juveniles for release on existing aquaculture – this could reduce or eliminate the need for expensive new hatchery construction for enhancement programs, as long as appropriate broodstock management protocols are in place for conserving wild-stock genetics.
14. Wild [postlarvae] can provide an abundant, low-cost source of juveniles for stock enhancement programs – this can sometimes be an effective way to reduce costs and eliminate genetic issues; successful scallop enhancement in Japan is based on collection of wild seed stock.
15. The costs of restocking can be reduced greatly for some species by relocating adults to form a viable spawning biomass – rebuilding spawning aggregations by concentrating broodstock can be effective for depleted stocks with limited larval dispersal, but care must be taken to avoid comingling different stocks (i.e., avoid translocation of exogenous genes).

Improving Survival in the Wild

16. Predation is the greatest hurdle to survival of released juveniles – care must be taken to understand ecology of the species and ecosystem at the release site and pilot experiments are needed to develop optimal release strategies to maximize survival.
17. Excessive releases of juveniles cause density-dependent mortality – density has a strong effect on growth and survival in the wild; planning release magnitude must take into account the carrying capacity at release locations. This requires

adaptive management and an experimental framework for releases.

18. Small-scale experiments to test methods for releasing juveniles can give misleading results – "commercial scale" releases are needed to test assumptions made from small-scale release experiments.
19. Good survival of released juveniles at one site is no guarantee that the methods can be transferred to other sites – stocking effectiveness will vary with release location and what works at one site may not be effective at another.

Other Manipulations to Increase Abundances

20. Artificial habitats can be used to increase the carrying capacity for target species – and may enable increased production at release sites where there are resource (food, refuge, space) limitations.
21. Yields of some species can be increased by providing suitable settlement habitat and redistributing juveniles from areas of heavy settlement – for example, redistribution can be used to reduce density effects and increase probability of successful recruitment when moved to a location with greater availability of food, refuge, or settlement habitats. But care must be taken to avoid genetic hazards associated with comingling stocks.

Examples of Progress Made in Marine Enhancement

As science and constructive debate have advanced in this field, there are many signs of progress. Some explicit examples of progress made in marine enhancement over the past couple of decades are presented below, ranging in scale from local experimental investigations of release strategies and density-dependent effects on hatchery and wild stocks (e.g., [100]) to documented replenishment impact in large-scale enhancement efforts (e.g., [101, 102]). This is but a sample of examples and is by no means a comprehensive list. There are many more examples in the peer-reviewed proceedings from the ISSESR and other stock enhancement conferences [41–53] and other journal articles.

1. Adoption of a science-based responsible approach to marine stock enhancement has now become widespread, resulting in a much more assessment-driven and precautionary approach than ever before (a few examples include Refs. [4, 6, 10, 12, 20, 22, 27–29, 33, 37–39, 59–61, 68, 69, 72, 75, 84, 86, 87, 89, 96, 103–106]). This has been enabled, in part, by advances in tagging technology (e.g., [8] and see examples in [9, 56]) and in development of new marine aquaculture technologies that can now provide juvenile fishes for marine enhancement research.
2. Networking of Scientists involved in this rapidly advancing field has been fostered by various symposia and working groups, for example, the World Aquaculture Society Working Group on Stock Enhancement and the scientific committees for the International Symposium on Stock Enhancement and Sea Ranching (www.SeaRanching.org).
3. There is a much better appreciation of the importance of managing marine fishery enhancements from a fisheries management perspective (e.g., [6, 59, 107]).
4. New tools are available for modeling stock enhancement effects and effectiveness [10, 82, 108–110].
5. At least two experimental field studies have now been conducted to evaluate density-dependent interactions of stocked hatchery and wild fish; these provide evidence that increased production can be achieved in juvenile nursery habitats without displacing wild fish, but not necessarily without displacing some of the hatchery fish [33, 100].
6. There is now clear evidence and a prescription of techniques for improving post-release survival (often with a doubling effect or more) of stocked marine fishes, and optimizing release strategies to maximize stocking efficiency and control impacts (e.g., [26, 36, 37, 39, 60–62, 70, 72, 100–115]). There is also ample evidence that in habitats with limited carrying capacity or intense predation, regardless of release strategy used, little can be done to improve survival of hatchery fish and stocking simply cannot increase production [106, 116, 117].
7. It is now fairly clear that marine enhancements may be cost effective only if (a) the supply of recruits is generally limiting, (b) there is adequate habitat to support an increased supply of juveniles, (c) cultured juveniles represent a large

portion of recruitment, (d) fishing is regulated appropriately, and (e) other management measures (catch regulations and habitat restoration) are insufficient to restore catch rates [96].

8. Stock enhancement of some species of marine finfish has been successful at the scale of large bays, for example, Hirame flounder and red sea bream in Japan [72, 106] when there is sufficient carrying capacity at release sites. Carrying capacity varies considerably among release sites, and thus must be evaluated and taken into account using monitoring and adaptive management for each release site.
9. Scallop sea ranching has been a large success in Japan, New Zealand, and China, where property rights and large ocean leases have created strong incentives for careful management by fishermen and owners of the sea ranching operations [72, 101, 102, 118]. For example, near Dalian, China, Zhangzidao Fishery Group leases 2,000 km^2 of ocean-bottom-to-ocean-surface for sea ranching. In 2010, Zhangzidao harvested an average of 150 t/day of ocean scallops from their sea ranching operations (over 50,000 t/year) (Wang Qing-yin, personal communication).
10. Property rights have also provided incentives for bivalve culture in the State of Washington, USA, where clam sea ranching operations have remained economically and environmentally sustainable for over three decades [119].
11. Pilot experiments with black bream in an Australian estuary have documented quite good survival and recruitment to the fishery. The latest phase of this project reveals strong rationale for long-term monitoring of enhancement impact [87, 120].
12. Restocking success with red drum in a South Carolina estuary [77, 121]. Pilot experiments revealed surplus productive capacity in the Ashley River in South Carolina, where fishery landings of red drum were doubled over a few years.
13. Pilot experiments to evaluate blue crab enhancement potential in Maryland and Virginia led to improvements in traditional fishery management, with information learned through stocking research [70, 114]. Pilot experiments can be used to provide critical information on the natural ecology, life history, and environmental requirements of valuable marine species [122].

Future Directions

Over the past two decades, there has been a rapid expansion of knowledge about marine fisheries enhancement systems and the effects and effectiveness of stocking a wide variety of marine organisms for sea ranching, stock enhancement and restocking. Many gaps in knowledge have now been filled. Well thought out approaches now provide a roadmap for effective use of enhancements. When models show potential for stocking, efforts to deploy marine enhancements can be successful if the principles in the roadmap are carefully employed. The basic reason that marine enhancement programs do not have more of a track record of success stories yet is that implementing them well is a complex endeavor that demands attention to multiple factors spanning many disciplines. Rarely have these been pulled together in an enhancement program. The Hatchery Reform Project in the Pacific Northwest USA, which includes an independent scientific review panel ("Hatchery Scientific Review Group") is a good example [123]. Because of their efforts, salmonid hatchery reforms now underway are bringing many of the principles of the Responsible Approach into play. The Norwegian PUSH program is another good example. In that case, information gained from quantitative assessments of enhancement showed that stocking would not be an economical way to enhance cod in Norway, thus saving years of wasteful spending that could have occurred there, had monitoring and adaptive management not been a central part of the enhancement system.

Successful examples of fisheries enhancement are truly group efforts, involving stakeholders, agency officials, and individuals with expertise in the principal sub-disciplines needed. Suffice to say that at this point in time few, if any, marine fisheries enhancement programs have enlisted all of the key elements of the Responsible Approach and Code of Responsible Conduct. But these principles are now well described and laid out in a systematic manner. It is reasonable to expect that if the Responsible Approach is used as the blueprint for planning and executing enhancements, and if the initial appraisal and goal setting stage indicates moving ahead, then there is ample opportunity for success in applying marine fisheries enhancements, as long as dedicated attention is focused on applying each of the key elements.

So how will marine enhancement advance to the next level – emergence of a rapidly growing body of success stories in restocking, stock enhancement, and sea ranching? Listed below are a few factors that are now needed to transition this field to the next level, where marine enhancements are well integrated into resource management systems and used wisely and appropriately.

Enabling Factors for Increasing Successful Marine Enhancements

1. *Greater awareness is needed among all stakeholders of the issues, pitfalls, progress, and opportunities in this field.* The concepts underlying effective enhancements need to be translated into lay language and used to inform stakeholders. This will help all stakeholders recognize the various issues and parameters needed for effective enhancements. Pivotal among stakeholders are public officials who fund enhancement programs, as they need to understand what it takes to develop an effective program or reform existing ones. New enhancement programs that may not be funded well enough to implement all of the key principles in the Responsible Approach would do well to use the results of Stage 1 in Table 3 to document the potential for success, but not proceed beyond Stage 1 until adequate funding is available.
2. *Use of Adaptive management is one of the most important principles for guiding successful enhancement programs.* Active adaptive management [91] is critical for gauging the effectiveness of, improving, and managing fisheries systems in the face of uncertainty. However, it is often dismissed by enhancement programs or given low priority for lack of funding or when enhancement is viewed as a quick fix. But, this important principle is used to optimize release strategies, to identify and deal with ecological or genetic impacts on wild stocks, to refine the enhancement process and identify the results of improvements, to evaluate and improve progress towards goals and objectives, and to monitor and improve economic impact. Active adaptive-management is an essential component of managing enhancement programs; it empowers management teams to understand and control the impacts of enhancements well. Without it, enhancement programs at best rely on hope to achieve their potential (but cannot) and at worst are doomed to failure. Australia is employing active adaptive management principles early in the development stage as part of ongoing work to evaluate enhancement potential for a wide range of species [124].
3. *Adapt the Responsible Approach to local circumstances.* The Responsible Approach is purposely vague on how to implement it. This is partly because not all elements are needed under all situations, but most will be. Fitting the process to particular circumstances is in itself a key part of implementing the Responsible Approach by engaging the various stakeholders in planning [6]. As progress continues in this field, additional principles will emerge that need to be included, for example, to account for needs of regional fishery management plans in response to climate change.
4. *Seek assistance from established workers in the field.* For new and developing enhancement programs, or existing ones seeking to design and implement reforms, there is a broad and expanding network of workers in this field who could be queried for advice on various enhancement issues. The ISSESR website is a good source for identifying individuals with specific kinds of expertise, by perusing presentation abstracts or locating published proceedings from past ISSESR conferences [125]. If researchers or workers in the field are contacted, but do not have time to provide advice, they usually will help identify others who could.

This entry may help expand awareness among fishery stakeholders, other natural-resource stakeholders, scientists, and fishery managers alike about the pitfalls, challenges, and progress made in using marine hatchery releases as one of the tools in resource management and seafood production. Readers are referred to the articles and symposium proceedings cited herein to gain a better understanding of the issues, lessons learned, and progress.

The debate focused on enhancement is a healthy one, for it is fostering steady improvements and reforms in existing programs, and careful planning and design in new ones. With each advance made, the potential seen by our forefathers to use hatcheries as a tool for recovering depleted stocks, increasing abundance in recruitment-limited stocks, and producing seafood by sea ranching is coming closer to fruition. One of the greatest lessons learned from the past is that the emphasis on expanding hatchery fish production for marine enhancement should not be allowed to take the focus off of the objective – increasing yields in fisheries and recovering stocks in restoration programs. Clearly, marine fisheries enhancement is a strong tool to add to the fishery management toolbox. But only careful analysis of conditions of the wild stock and the fishery will guide when and where it is appropriate to use enhancements in addition to other management options, and when to stop. As Albert Einstein once said, "a perfection of means, and confusion of aims, seems to be our main problem." With the focus shifted to outcomes in marine enhancement programs, the appropriate means should fall into place, aided by healthy debate and prescriptions for a responsible approach to marine fisheries enhancement.

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Marine Fisheries Enhancement: Coming of Age in the New Millennium. Table 1 The ten principles of a responsible approach to marine stock enhancement [4]

1	Prioritize and select target species for enhancement by ranking and applying criteria for species selection
2	Develop a management plan that identifies how stock enhancement fits with the regional plan for managing stocks
3	Define quantitative measures of success to track progress over time
4	Use genetic resource management to avoid deleterious genetic effects on wild stocks
5	Implement a disease and health management plan
6	Consider ecological, biological, and life history patterns in forming enhancement objectives and tactics; seek to understand behavioral, biological, and ecological requirements of released and wild fish
7	Identify released hatchery fish and assess stocking effects on the fishery and on wild stock abundance
8	Use an empirical process for defining optimal release strategies
9	Identify economic objectives and policy guidelines, and educate stakeholders about the need for a responsible approach and the time frame required to develop a successful enhancement program
10	Use adaptive management to refine production and stocking plans and to control the effectiveness of stocking

Marine Fisheries Enhancement: Coming of Age in the New Millennium. Table 2 Code of responsible conduct for marine stock enhancement [5]

• Make certain that management priorities and acceptable trade-offs are absolutely clear
• Do careful stock assessments to show that the target stock is recruitment overfished or can no longer rear successfully in the wild
• Show that enhanced fish can recruit successfully in the wild
• Show that total abundance is at least initially increased by the hatchery fish contribution
• Show that fishery regulations are adequate to prevent continued overfishing of the wild population, unless there has been an explicit decision to “write off” the wild population
• Show that the hatchery production system is actually sustainable over the long run, when it is to be a permanent component of the production system

t3.1 **Marine Fisheries Enhancement: Coming of Age in the New Millennium. Table 3** The updated responsible approach (From [6])

t3.2	Stage I: Initial appraisal and goal setting	
t3.3	1	Understand the role of enhancement within the fishery system [*new*]
t3.4	2	Engage stakeholders and develop a rigorous and accountable decision making process [*new*]
t3.5	3	Quantitatively assess contributions of enhancement to fisheries management goals
t3.6	4	Prioritize and select target species and stocks for enhancement
t3.7	5	Assess economic and social benefits and costs of enhancement
t3.8	Stage II: Research and technology development including pilot studies	
t3.9	6	Define enhancement system designs suitable for the fishery and management objectives [*new*]
t3.10	7	Design appropriate aquaculture systems and rearing practices [*new*]
t3.11	8	Use genetic resource management to maximize effectiveness of enhancement and avoid deleterious effects on wild populations.
t3.12	9	Use disease and health management
t3.13	10	Ensure that released hatchery fish can be identified
t3.14	11	Use an empirical process for defining optimal release strategies
t3.15	Stage III: Operational implementation and adaptive management	
t3.16	12	Devise effective governance arrangements [*new*]
t3.17	13	Define a management plan with clear goals, measures of success, and decision rules
t3.18	14	Assess and manage ecological impacts
t3.19	15	Use adaptive management

Marine Fisheries Enhancement: Coming of Age in the New Millennium. Table 4 Key areas of expertise needed in marine fisheries enhancement t4.1

• Fisheries science	t4.2
• Fisheries management	t4.3
• Adaptive management	t4.4
• Marine aquaculture	t4.5
• Population genetics	t4.6
• Aquatic animal health	t4.7
• Population ecology	t4.8
• Behavioral ecology	t4.9
• Community ecology	t4.10
• Resource economics	t4.11
• Social science and institutional analysis and design	t4.12
• Statistics and experimental design	t4.13
• Tagging technology	t4.14
• Communications and outreach	t4.15

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