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Evolving Context and Maturing Science: Aquaculture-Based Enhancement and Restoration Enter the Marine Fisheries Management Toolbox

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Abstract

Aquaculture-based enhancement of marine fisheries includes sea ranching, stock enhancement, and restocking. A rapidly evolving context and maturing science base have effectively put these approaches into the fisheries management toolbox. Among the contextual factors are (1) a rapid expansion of captive breeding and domestication to new marine species, (2) fisheries governance systems that address the common dilemma, and (3) global environmental change impacts on coastal fisheries that increasingly call for active approaches to maintaining or increasing fisheries yields and ecosystem services. The science base of marine restocking, stock enhancement, and sea ranching continues to advance rapidly and has now reached a point where it is becoming possible to assess the likely contribution of such approaches to fisheries management goals prior to major investments being undertaken and to design enhancement programs effectively and responsibly where good potential is judged to exist. This signifies an important transition of marine fisheries enhancement from an exploratory, research-oriented endeavor to a tool in the fisheries management tool box.

Keywords: rights-based fisheries management, individual quotas, hatcheries, coastal zone

Introduction

Fisheries and aquaculture supply some 20% of the world's animal animal protein, employ an estimated 55 million people, and also provide recreational opportunities to several hundred million people (Cooke and Cowx, 2006; Worm et al., 2009; FAO, 2012). Yields from capture fisheries have remained relatively constant for over a decade, and many fisheries are either fully exploited or overexploited, while others are recovering from historical over- exploitation (FAO, 2012; Worm et al., 2009). Aquaculture-based fisheries enhancement is a set of management approaches that involve the release of cultured organisms to enhance or restore fisheries. Specific approaches include sea ranching (releases for direct recapture), stock enhancement (continued releases into self-recruiting wild stocks), and restocking (temporary releases aimed at rebuilding a self-recruiting stock; Bell et al., 2008a; Lorenzen, 2008b). Besides control of fishing effort and habitat protection or restoration, aquaculture-based enhancement is a third principal means by which fisheries can be sustained and improved.

Following unsuccessful and eventually abandoned attempts at enhancing marine fisheries through releases of fertilized eggs or larvae in the early 20th century, the scientific study of marine stock enhancement started in earnest in the 1970s (Leber 2013 and references therein). The International Symposia on Stock Enhancement and Sea Ranching held in Norway in 1997, Japan in 2002, the United States in 2006, and China in 2011 have played an important role in shaping the study of marine fisheries enhancements into a coherent and rapidly advancing discipline. Proceedings of the symposia have been published in two books (Howell et al., 1999; Leber et al., 2004) and as special issues of *Reviews in Fisheries Science* (Volume 16, Issues 1–3, 2008; and the current issue). These proceedings have been instrumental in reviewing and synthesizing scientific progress based on symposium presentations, exchange of ideas among delegates, the wider literature, and in identifying directions for further research. In keeping with this tradition, the present lead article aims to review scientific progress and wider developments in the field since the last such article was published (Bell et al., 2008).

This article begins by briefly reviewing some developments in aquaculture, fisheries, and coastal ecology that provide important context for the future potential of aquaculture-based enhancement and restoration. Then key developments in the science base of enhancements are highlighted before reviewing some case studies and their use of scientific principles. The article closes by highlighting recent policy developments before offering some conclusion and research recommendations.

Evolving context

The Number of Marine Species Successfully Reared in Aquaculture Continues to Grow Rapidly

Aquaculture now contributes about half the aquatic animal food available for human consumption and is expected to grow further to meet the future demand (Bostock et al., 2010, FAO, 2012). The number of marine animal species reared in aqua- culture has increased rapidly. Of 250 species of marine animals cultured for food by 2007, 97% were brought into culture in the past century and about 20%

in the past decade (Duarte et al., 2007). Many more marine animals are cultured for ornamental or research purposes. Not all cultured marine animals have had their lifecycle closed in captivity or have been fully domesticated (Bilio, 2008; Lorenzen et al., 2012), but these figures nonetheless illustrate that aquaculture technologies are becoming available for a rapidly growing number of marine species. Efficient aquaculture production is a prerequisite for aquaculture-based fisheries enhancement or restoration initiatives. Development of commercial aquaculture can reduce the costs of seed organisms for stocking and make them readily available to fishers and other stakeholders who may lack the skills or resources to develop culture systems, thus enabling resource-user led enhancement initiatives (Bell, 1999; Lorenzen, 2008b).

New Fisheries Governance Systems Limit Access and Provide Incentives for Resource Conservation and Enhancement

Governance systems in many fisheries have changed radically over the past one to two decades, increasingly replacing open access to coastal fisheries resources with restricted access mediated by individual quotas, territorial use rights (TURFs), or individual licenses (Chu, 2009; Lorenzen et al., 2010b; Loneragan et al., 2013). The new governance regimes are de- signed principally to limit exploitation of fisheries to sustain- able levels but may also provide incentives for active resource enhancement or restoration by restricting access and allowing those who invest in the resource to benefit from their investment (Lorenzen, 2008b).

Increasing Importance and Recognition of Fisheries Systems at the Interface of Capture Fisheries and Aquaculture

As a result of the proliferation of aquaculture technologies as well as exclusive use rights to marine resources, many coastal fisheries are undergoing a subtle transformation from “hunting” to “farming” systems. Intermediate systems that combine attributes of capture fisheries and aquaculture are emerging as an important third category of aquatic resource systems. Such systems have long been present in inland areas where aquaculture technologies were developed earlier and exclusive rights to aquatic resources are common, for example in Southeast Asia (Amilhat et al., 2009a,b). More recently, the emergence of such intermediate systems, including aquaculture-based fisheries enhancements, has been observed and recognized in the marine realm (Anderson, 2002; Klinger et al., 2012).

Impacts of Population Growth and Global Environmental Change Are Projected to Exceed the Mitigating Capacity of Traditional Fisheries Management and Conservation Tools

Pressures on coastal fisheries resources are predicted to increase substantially over the next few decades, particularly in the tropics (Wilson et al., 2006; Duarte et al., 2009; Merino et al., 2012; Worm and Branch, 2012). Key drivers include (1) population growth and economic development, which together will greatly increase demand for both seafood and marine recreation; (2) local habitat alteration linked to coastal population growth; (3) other effects of global climate change and ocean acidification, and (4) fresh-water limitations to the expansion of protein production through land-based agriculture, leading to greater reliance on seafood as the earth approaches human-carrying capacity. Traditional fisheries management and conservation measures (such as marine protected areas) play an important role in helping to sustain fisheries in the face of these changes but will likely be insufficient to fully mitigate the broad changes arising through coastal development and global change (e.g., Armstrong et al., 2010, Hines et al., 2010; Hollowed et al., 2013). Aquaculture has a key role in filling the gap between seafood demand and stagnant or declining production from capture fisheries, but sustaining this trend will require closing the production cycle and reducing the demand for inputs harvested from capture fisheries or produced in agriculture (Duarte et al., 2009; Bostock et al., 2010). In the face of these challenges, aquaculture-based enhancement and restoration approaches are likely to play an increasing role in sustaining food and recreational fisheries and in restoring biodiversity and ecosystem functioning. Such approaches have long played a significant role in highly modified freshwater systems (Welcomme and Bartley, 1998; Paquet et al., 2011; Brummett et al., 2013).

Maturing science

Key elements of the science base have now matured to the extent that it is becoming possible to predict the outcomes of enhancements and evaluate the likely utility of such approaches vis-à-vis alternative fisheries management measures. This is a crucial development because it means that enhancements can be realistically appraised prior to major investments being undertaken. Several recent advances have made this possible: the development and use of stock assessment models that allow quantitative assessment of enhancements and alternative or additional fisheries management options, improved understanding and quantification through models and meta-analyses of impacts of culture practices and genetic management on post-release fitness of cultured juveniles, use of telemetry and other tag techniques that allow detailed evaluation of post-release performance and interactions, and adoption of systems approaches to the development and reform of enhancements. Many of these advances are rooted in major and long-running enhancement research programs, including those on cod in Norway (Svåsand et al., 2000; Pacific salmon in North America and Japan (Naish et al., 2007; Miyakoshi et al., 2013), various marine fish species in Japan and Australia (Kitada and Hishino, 2006; Loneragan et al., 2013), and blue crab in the United States (Zohar et al.,2008), but have only recently developed into a coherent and predictive enhancement science.

Aquaculture and Genetic Management

Efficient aquaculture production of seed organisms that perform well under natural conditions is a prerequisite for effective and economically viable enhancement or restoration. Unfortunately, cultured organisms often perform poorly in the wild due to developmental and genetic effects of culture on many aspects of their biology. Lorenzen et al. (2012) provided an integrative review of these effects and their implications for fisheries enhancement and restoration, pointing out that different uses of organisms may call for different culture and genetic management approaches and place different relative weights on culture efficiency and quality of the release organisms. In their genetic analysis of a founder population for a catfish restocking program, dos Santos Neto et al. (2013) illustrated this differentiated approach to stock-management goals. While the captive founder population showed high diversity and low relatedness, it also exhibited high distinctiveness from extant wild populations in the focal areas, leading the authors to determine that the brood stock could be used to support restocking/re-introduction in areas where the wild population has collapsed but not enhancement of existing wild populations.

Meta-analyses are increasingly being used to distill generalizations about the genetic effects of enhancements and thereby improve the predictability of such effects in the evaluation of planned enhancements (Araki et al., 2008; Fraser, 2008). Such meta-analyses of course rely on the availability of well-designed genetic impact assessments for individual enhancements that remain relatively rare in marine systems (but see, e.g., the long-term studies conducted as part of the Norwegian sea ranching research program [Jørstad, 2004; Agnalt, 2008]). Progress has also been made in assessing options for minimizing unintended fitness consequences of cultured fish on wild populations through use of combined genetic and demographic models (Baskett and Waples, 2013).

Aiding the transition of hatchery-reared organisms into the wild through such acclimatization procedures as soft release or conditioning is an important consideration that can greatly increase the effectiveness of releases (Olla et al., 1998; Brown and Day, 2002; Salvanes and Braithwaite, 2006). Holding fish in cages at release locations prior to release is emerging as a consistently effective and relatively simple acclimatization procedure. This allows organisms to explore their new habitat in the relative absence of predation pressure and to develop such skills as burial and feeding abilities that have been shown to improve post-release survival, e.g., in cultured juvenile flatfish (Walsh et al., 2013) and blue crabs (Young et al., 2008). Positive acclimation effects on survival have also recently been reported in common snook (Brennan et al., 2006) and California white sea bass (Hervas et al., 2010).

Release Strategies and Post-Release Ecology

Release strategies (habitat, size, season, etc.) greatly influence immediate post-release survival and ecological interactions of hatchery fish in the wild and have long been a focus of fisheries enhancement research (e.g., Hines et al., 2008; Chin et al., 2013). The availability of telemetry techniques that allow continuous monitoring of large numbers of tagged, released animals has revolutionized the design of release experiments and provided far more detailed information on post-release ecology than could traditionally be obtained from recaptures alone (e.g., Taylor et al., 2006; Pursche et al., 2013; Kawabata et al., 2008). Several studies in this volume illustrate the rich information that can be gleaned from telemetry studies. Green et al. (2013) examined behavioral interactions between wild and translocated rock lobster and found no interactions likely to lead to displacement of lo- cal resident stocks by translocated lobsters. Taylor et al. (2013b) used acoustic telemetry to monitor emigration and space utilization in juvenile mulloway at different release densities and were able to show that the fish distributed themselves across habitats of different quality as expected under the ideal free distribution, and that higher release densities lead to a greater proportion of fish occupying suboptimal habitats. The data obtained from such telemetry studies on site fidelity and movement can also provide crucial information for the design of control-impact studies by identifying the appropriate spatial extent of impact and control areas (Lee et al., 2013). Currently telemetry has great utility for studying post-release ecology of stocked adults, sub-adults, and advanced juveniles but cannot be applied to smaller individuals without serious tag loss and possible mortality.

Population Dynamics and Quantitative Assessment

Quantitative research on the population dynamics of aquaculture-based enhancement and restoration measures is central to assessing their contribution to fisheries management goals (Lorenzen, 2005). Long-term experimental studies on the dynamics of pilot-scale abalone enhancements are reported in this volume by Hart et al. (2013a,b) and Chick et al. (2013). The studies are remarkable for not only providing direct estimates of key growth and mortality parameters but for experimentally estimating carrying capacity and testing for displacement of wild individuals by hatchery organisms. Studies of this nature are not only crucial to assessing enhancement potential but also provide valuable information on the dynamics of wild stocks that could not easily be obtained without the experimental manipulations carried out with the help of hatchery organisms (Miller and Walters, 2004).

Modeling remains a key tool for analyzing population dynamics, and this volume contributes to the suite of models available for the development of enhancement programs. Taylor et al. (2013a) present a food consumption model for stocked populations to assess trophic limits to stocking density and related ecological impacts. Such trophic models pro- vide an important complement to population models already available for assessing enhancement programs. Population dynamics modeling has been used extensively in the evaluation of salmonid hatchery programs as part of the hatchery reform process in the northwestern United States (Paquet et al., 2011), the evaluation of prawn enhancement in Western Australia (Loneragan et al., 2004), and the EnhanceFish program (Medley and Lorenzen, 2006) and has been applied to numerous enhancement projects throughout the world. These modeling studies have identified many improvements to hatchery programs that would simultaneously increase harvest opportunities and help conserve wild stocks.

Three recent studies on compensatory processes in fish populations have important implications for fisheries enhancements. A meta-analysis by Lorenzen (2008a) showed through that both density-dependent survival in juveniles and density-dependent growth in recruited fish are important mechanisms of population regulation in most fish populations, with juvenile mortality being the strongest source of compensation in most but not all populations. This supports the idea that stocking of larger juveniles (to avoid the life stages where survival is most strongly density de- pendent) may allow moderate enhancement of abundance in recruited fish that will, however, ultimately be limited by compensatory effects in fish growth (see also Gardner et al., 2013). The size or age at which density dependence in survival is strongest in fish and other aquatic animals is poorly quantified but of obvious interest. A detailed study on density-dependent processes in laboratory populations of zebrafish points to broadly consistent lifetime patterns of density-dependent processes within fish populations that may be invariant to maximum body size, with the strongest density dependence in survival occurring when juveniles are about 10–15% of the species' maximum length (Hazlerigg et al., 2012). In another study of direct relevance to certain enhancement systems, Smith et al. (2013) examined how intraspecific competition can scale population regulation through self-thinning, due to the differential allocation of energy to activity or growth and consequent changes to the energetic efficiency of self-thinning cohorts. These studies further understanding of the way in which compensatory processes act at different life stages, allowing better assessment of the scope of fisheries enhancement and the efficacy of different release strategies from a population dynamics perspective.

Bio-Economic Modeling and Enhancement Systems Analysis

Bio-economic modeling is key to appraising the potential of enhancement or restocking initiatives vis-à-vis other fisheries management measures and evaluating the cost–benefits of release programs (e.g., Lorenzen, 2005; Ye et al., 2005). The publication and use in decision making of realistic bio-economic models is therefore an important step in putting enhancements into the fisheries management toolbox. For example, the results of bioeconomic modeling for releases of tiger prawns *Penaeus esculentus* in Exmouth Gulf, Western Australia, contributed to the decision by the fishing industry not to progress to large pilot scale releases of (Ye et al., 2005). Hart et al. (2013c) used a bio-economic model conditioned on detailed experimental data (Hart et al., 2013a,b) to assess the economic viability of abalone stock enhancement as a long-term strategy,. The model shows that abalone enhancement may be a viable management option and would generate the greatest benefits if fishing mortality would be moderately reduced. Prince (2013) evaluated the economic feasibility of restocking abalone stocks depleted by dis- ease, concluding that there is likely no advantage to restocking over natural recovery unless recruitment in the depleted stock is subject to depensatory processes (in which case restocking would be beneficial, but translocation of wild adults is predicted to be more beneficial than stocking of cultured juveniles).

Camp et al. (2013) conducted a broad-based, qualitative analysis of interactions between the resource, stakeholders, and the governance system in determining outcomes of a marine recreational fisheries enhancement program for red drum in Florida, USA. This study suggests that a fundamental tradeoff remains between short-term socio-economic and ecological objectives in enhanced recreational fisheries because stocking of hatchery fish is likely to result in at least partial displacement of wild fish through biological interactions as well as increased fishing pressure. The shape of this tradeoff depends on biological attributes of the stock and on angler motivation and behavior. It can be modified through management measures that reduce interactions between wild and hatchery fish during key stages of their lifecycle and at harvest and by changes in angler motivations or behaviors or in governance arrangement. Contrary to the perception of enhancement as a “quick fix,” successful use of the approach in the marine recreational fishery is likely to require sophisticated stock management and adaptation in governance. Elsewhere, Van Poorten et al. (2011) developed a model of a coupled social-ecological system of recreational fisheries in which managers support naturally fluctuating stocks by stocking fish in response to harvest-driven satisfaction of resource users. They show that a stocking-based management panacea with eventual replacement of wild by hatchery fish can result in this system when fishers remember past harvest experiences and encourage stocking at times when current experiences fall short of historical levels.

Development and reform of enhancements

Pilot Studies on Tropical Small-Scale Enhancements

As pointed out above, the tropical coasts and coastal communities are projected to experience substantial degradation in their fisheries resource base over the coming decades. Aquaculture- based enhancement and restoration approaches may help to sustain ecosystem services, food production, and livelihoods in these areas. While past International Symposia on Stock Enhancement and Sea Ranching (ISSESR) volumes (Howell et al., 1999; Leber et al., 2004; Bell et al., 2008b) have documented many pilot studies in temperate systems, this volume contains several pilot evaluations of small-scale enhancement and restocking approaches for tropical coasts. Dolorosa et al. (2013a,b) evaluated the potential for restoring overexploited stocks of *Trochus* (topshell) by translocating wild animals and rearing hatchery animals to a larger release size. They conclude that the translocation of wild *Trochus* into a network of marine reserves has potential for restoring populations. The sub-tidal cage culture of *Trochus* was identified as a suitable approach for on-growing hatchery animals to a larger size, but the performance of such animals after release is yet to be evaluated. Junio-Menez et al.

(2013) and Lebata-Ramos et al. (2013) demonstrated that hatchery sea cucumber and abalone stocked on Philippine reefs can survive, grow, and lead to increases in harvestable stocks. While these studies demonstrate the bio- logical feasibility of small-scale ranching systems, further development associated with the optimal release and harvesting strategies and economic feasibility are required.

Evaluating and Reforming Operational Enhancements

Evaluations of operational enhancements are important for identifying ineffective or damaging initiatives. More importantly, they often can help identify substantial improvements in effectiveness and economic efficiency when conducted in an analytical fashion, so that alternative management practices can be explored. This is most strikingly demonstrated by the quantitative evaluations conducted as part of the hatchery reform process for salmonid release programs in the Pacific Northwest of North America (Paquet et al., 2011).

Three different approaches to evaluation of operational enhancements are illustrated in this volume: detailed monitoring and evaluation of stocking in an age-structured framework, statistical analyses of long-term landings data, and a qualitative/quantitative review of historical changes in enhancement practices and returns. Gardner et al. (2013) examined ten years of data on catches of stocked and wild *Acanthophagus butcheri* (a sparid) in an Australian estuary post-restocking and demonstrated that restocking has resulted in a substantial contribution of stocked fish to commercial catches of the species, while eliciting a compensatory growth response in wild fish. Hamasaki and Kitada (2013) analyzed long-term data to estimate impacts of climatic factors and hatchery stocking on kuruma prawn (*Penaeus japonicus*) catches, concluding that climate was an important driver of kuruma prawn catches. While contributions of the hatchery program to fisheries catches had been low, stocking has the potential to stabilize catches in the face of wild population decline due to climate change. In an extensive historical review of salmon ranching in Hokkaido, Japan, Miyakoshi et al. (2013) concluded that the hatchery programs have been successful in increasing commercial catches while conserving genetic diversity and will likely remain an important management tool. Conservation of the remaining wild salmon populations, however, has been recognized as an additional priority and this may force restrictions on the hatchery operations in the future.

Guidance and Policy Frameworks

There have been several significant developments in terms of best practice guidance and policy. The most widely accepted guidance framework for developing enhancements, the responsible approach (Blankenship and Leber, 1995) has been comprehensively updated by Lorenzen et al. (2010a). The up- dated responsible approach retains key elements of the original approach but places enhancements firmly in their fisheries management context. The updated approach emphasizes evaluation (through stock assessment modeling and other techniques) of a proposed enhancement's likely contributions to fisheries management goals at an early stage, prior to major investments in facilities or technology development. The approach of screening enhancements alongside alternative fisheries management options such as new harvest regulations and the availability of modeling tools for doing so are crucial to the entry of stock enhancement and restocking into the fisheries management toolbox. The hatchery reform processes in the Pacific Northwest of the United States adopted and followed their own principles, which are similar to those set out in the updated responsible approach, illustrate the power of fisheries management approaches that fully integrate harvest regulations, habitat, and hatchery programs in a common assessment framework (Paquet et al., 2011).

In 2010 the FAO finalized its Guidelines for the Ecolabelling of Fish and Fishery Products from Inland Capture Fisheries (FAO, 2010). These guidelines, which also cover diadromous species, are the first FAO guidelines to define explicit criteria for ecologically sustainable enhanced fisheries. The substantive requirements stipulate in particular that enhancements must not result in a reduction of the naturally recruited stock components to levels below those associated with sustainable harvesting of this component in a capture fishery (typically the stock biomass at which the maximum sustainable yield is obtained).

The enactment of fisheries enhancement policies by national or state-level fisheries management agencies, for example in Australia (Loneragan et al., 2013), is another development that signifies the entry of aquaculture-based fisheries enhancement and restoration into the fisheries management toolbox. The significance of such policies is threefold: first, they constitute recognition of the approach as a management, rather than purely research activity; secondly, they identify (to a varying degree of specificity) the characteristics and limits to ecological impacts of enhancements that the jurisdiction is willing to consider; and thirdly, they set out clear procedures by which proposals for enhancement activities can be made and evaluated. The importance of the latter point, in particular, cannot be overstated, as it empowers a broad range of entities to propose and possibly develop enhancements.

Directions for research and conclusions

Several areas emerge as key research directions:

- Meta-analyses of post-release performance and population dynamics of enhanced fisheries hold potential for further improving the predictability of enhancement outcomes.
- Rigorous experimental evaluation of large-scale enhancement initiatives is crucial for assessing compensatory responses and ecological impacts that may not become evident in pilot-scale studies.
- Economic and social evaluation of enhancements versus alternative management options.
- Systematic exploration of the potential of enhancements to contribute to mitigation of global change impacts.

A rapidly evolving context and maturing science base have effectively put sea ranching, stock enhancement, and restocking into the coastal fisheries management toolbox. The contextual factors include a rapid expansion of captive breeding and domestication to new marine species, development of fisheries governance systems that address the commons dilemma, and global environmental change impacts on coastal fisheries that increasingly call for active approaches to maintaining fisheries yields and ecosystem services. The science base continues to advance rapidly and has now reached a point where enhancement systems can be designed effectively and their potential contribution to fisheries management goals quantitatively evaluated. This signifies a transition of marine fisheries enhancement from a research-oriented endeavor to a management-oriented endeavor. Enhancement policies are likely to be instrumental in bringing enhancement approaches into the management framework in a constructive and responsible manner.

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