Monterey Bay Aquarium®

Photo credit: Gerald Hulleza

# Marine stock enhancement

## Assessing shortfalls and opportunities

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## ACRONYMS

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| **BSC** | Blue swimming crab |
| **CPUE** | Catch per unit effort |
| **EBFM** | Ecosystem-based fisheries management |
| **FAO** | Food and Agriculture Organization of the United Nations |
| **GPS** | Global positioning system |
| **IAD** | Institutional Analysis and Development |
| **PDR** | [Lao] People's Democratic Republic |
| **OSMOSE-JZB** | Object-oriented Simulator of Marine ecOSystEms |

# Contents

# Executive summary

A growing human population and diminishing food supply, leading to the stagnation and overharvest of wild fisheries stocks, are the driving forces behind the development of management tools and innovative ideas for augmenting seafood production. One approach that has been utilized for more than a century (Molony et al., 2003) is "enhancement" – to increase fisheries production by releasing hatchery-raised juveniles into the wild. While this tool has had limited successes (e.g., salmon in Alaska), overall, failed projects outweigh successful ones, and many questions remain unanswered regarding the practicality, utility, and efficiency of this technique.

The use of stock enhancement has been primarily driven by managers and stakeholders, largely because it is an active rather than passive management method. Although this is popular, effective science and long-term monitoring are crucial to developing programs that minimize risk to ecosystems and maximize production, while supporting healthy wild populations (Lorenzen, 2014). Kitada (2020) reported that more than 26 billion juveniles of 180 marine species are released annually into the wild in 20 countries, yet the outcomes of these releases are inconclusive. Most of the efforts in Japan surveyed by Kitada (2020) also showed that stocking efforts were generally small; population dynamics remained unaffected by releases and were additionally constrained by the carrying capacity of the nursery habitat. Overall, most efforts did not provide a sufficient return on investment.

While the overall impact of existing crustacean enhancement programs may be minimal, the last two decades have seen some progress in the ability to assess the contribution of stock enhancement to seafood supply chains. Continued scientific research into lifecycles and ecosystem processes has enabled the evaluation of a new range of species and release strategies. In addition, new technologies for tagging and determining genetic contributions now allow for more detailed monitoring of these programs over time. There is also evidence that stock enhancement initiatives can demonstrate positive social impacts, such as increased participation in management decision making by fishermen and community members, particularly in areas where more traditional fisheries management tools have not been successful.

This review focuses on crab and other crustacean enhancement programs. Enhancement for this group is based on their high fecundity, significant mortality in the larval stage, and the transition to the benthic juvenile stages.

To date, the overall results of these enhancement efforts remain mixed and inconclusive; some small-scale pilots show promise, yet more than one nation has already heavily invested in large-scale enhancement programs without sufficient information or proof of concept. Careful design of any stock enhancement programs is critical to avoiding socioeconomic pitfalls or ecosystem damage.

This report highlights a number of important lessons learned on enhancement programs for crustaceans:

- Many stock enhancement efforts are not economically viable to maintain or bring to scale, and ultimately, project success or failure may depend on natural fluctuations in the environment as well as varying participant interest. Traditional management tools, including habitat improvements and effort control, have a better chance of restoring stock health.
- Stock enhancement may not work – many pilot projects demonstrate ambiguous results, and there are several examples where efforts did not result in the increased abundance of the target species. Additionally, concerns regarding potentially negative effects on target species (e.g., genetic dilution), other species, and the surrounding environment remain unaddressed.
- Long-term impacts remain difficult to track, and benefits observed in the near term (increased number of animals in an area) may not be maintained until the species recruits to the fishery. Short- and long-term monitoring must be conducted to document possible negative and positive impacts.
- Pilot trials with multiple life history stages are essential to understanding the best size at release as well as the ecological consequences for the site of release.
- Stock enhancement efforts should be carefully designed in combination with other management tools, and not be considered as a stand-alone solution.
- Stakeholder participation is key and necessary for any enhancement program. Identifying and agreeing upon clear objectives is a crucial part of this process – particularly with regards to how "project success" is defined.

This review found that despite a range of opinions in the literature, crab and crustacean management tools such as effort control and habitat improvements are much more likely to restore stock health when compared with stock enhancement techniques such as larval release or other strategies.

# Introduction

Ever since humans started to rely on the harvest of marine organisms as a source of food, money, and identity, we have struggled with how to balance our growing demands against the need to maintain sustainable fish populations and healthy ecosystems. The failure to protect our ocean resources has led to massive depleted areas, endangered or threatened species, and – in some cases – extinction (IUCN Red List, n.d.).

Sound fisheries management has occurred for millennia (Reeder-Myers et al., 2022), but with the advent of a focus on large boat fisheries of single species, specific management efforts – such as utilizing minimum mesh size proposed by Russell in 1942 – needed to be implemented. Following this, additional management tools have been developed, including different types of input controls, output controls, and various types of marine protected areas (Cochrane and Garcia, 2009). All these management techniques involve some sort of restriction of fishing effort – a challenging, expensive endeavor for managers, with a strong likelihood of negative impacts on the fishing community and local markets. One alternative, by its nature, does not impose restrictions – that of artificially enhancing stock size through hatchery-reared juveniles. This remains a hotly debated topic: many proponents view this as a quick fix for depleted stocks and supplementing weak year classes, while opponents point to the lack of evidence of success and point out that many of the more traditionally restrictive management tools can be avoided.

Early attempts at enhancement required larvae to be collected from the wild; however, there are significant concerns that this may lead to reduced natural production. With advanced technology and increased knowledge about lifecycles, animals can now be spawned in the laboratory and cared for through their critical growth periods with adequate food and shelter until they reach a viable size for release into the wild.

This trade-off between increased survival at release and the cost of maintaining larvae in captivity is a major driver for economic sustainability. The longer the animal is held, the more expensive it becomes. Most of these programs are government-operated and funded with taxpayer money; there is little to no incentive for private investment, given that the animals, once released, are available for all to catch. Stock enhancement is usually expensive, labor intensive, and most often conducted at a pilot scale. This has brought into question both the economics of these operations as well as the reduction of genetic variability, as the limited number of spawning stock are often retained and used repeatedly. Once released, it is difficult to follow the survival and growth of the animals given they are often too small for traditional tagging methods. However, new tagging methods, including genetic tools, are increasingly being developed and applied to allow for improved tracking and identification.

In the United States, concerns of overfishing American lobster, *Homarus americanus*, have led to various forms of intervention over more than 100 years. Between 1885 and 1920, more than 22 hatcheries operated in the Gulf of Maine and maritime Provinces of Canada for the express purpose of lobster enhancement, yet they did not contribute significantly to natural populations (Van Olst et al., 1980). Other methods to supplement natural populations, such as translocation of berried females to an area impacted by an oil spill in Rhode Island (French, 1999) were similarly unsuccessful, as landing in this area remains low. The one measure that was successful in maintaining a viable reproductive population of wild American lobster was protecting the berried females by not only landing them, but also marking them to prevent future harvests.

Overall, experimental designs still lack the capacity to test human-based enhancement of biomass through larval release rather than changes in natural productivity over time. Some pilots are never monitored for success or failure; some are followed only for short periods of time. Few projects are followed for more than a few years. Unless carefully designed, hatchery animals can wreak havoc in sensitive environments – competing for limited resources, changing the genetic diversity of the stock, introducing disease, attracting new predators, and depleting food supplies.

There have been a handful of cases that have deemed enhancement to be successful. Some have introduced novel approaches, such as varying hatchery release times to not compete with the wild stock or raising animals in new habitats. Objectives for stock enhancement can vary depending on the stakeholder, so measures of success will also vary accordingly. Lorenzen (2008) outlined a framework which takes a broad systems view and gives equal emphasis to the dynamics of both biological and human components. Non-biological objectives can include the economics of the fishery and social objectives such as supporting a recreational fishing activity or establishing better resource stewardship.

This white paper reviews the ecological theory behind enhancement and explores past efforts at species stock enhancement and restocking, particularly for portunid crabs in Southeast Asia.

# Marine stock enhancement: a global overview

Stock enhancement has been a popular choice for fisheries management, largely because of its perceived simplicity. The basic premise is that by producing and stocking fish, catch rates and fishing success will be maintained or increased (Molony et al., 2003); a preferred alternative to stricter, more traditional management tools. While there are many terms used to describe the release of cultured juveniles into coastal waters, the precise definitions we are using in this white paper are as follows (Bell et al., 2008):

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

**Restocking:** The release of cultured juveniles into wild populations to restore severely depleted spawning biomass to a level where it can once again provide regular, substantial yields.

**Sea ranching:** The release of cultured juveniles into unenclosed marine and estuarine environments for harvest at a larger size in "put, grow, and take" operation.

Between 1984 and 1997, 180 species were released by 64 countries (Kitada, 2018) in attempts at marine stock enhancement. By 2016, Kitada reports that a total of 187 species had been released by 20 countries. Japan has released the largest number of species (72), followed by Taiwan (24), the USA (22), China and South Korea (14), and Australia (7). Canada and Russia have released only salmon. The Pacific salmon hatchery release is one of the largest stocking programs in the world (Figure 1).

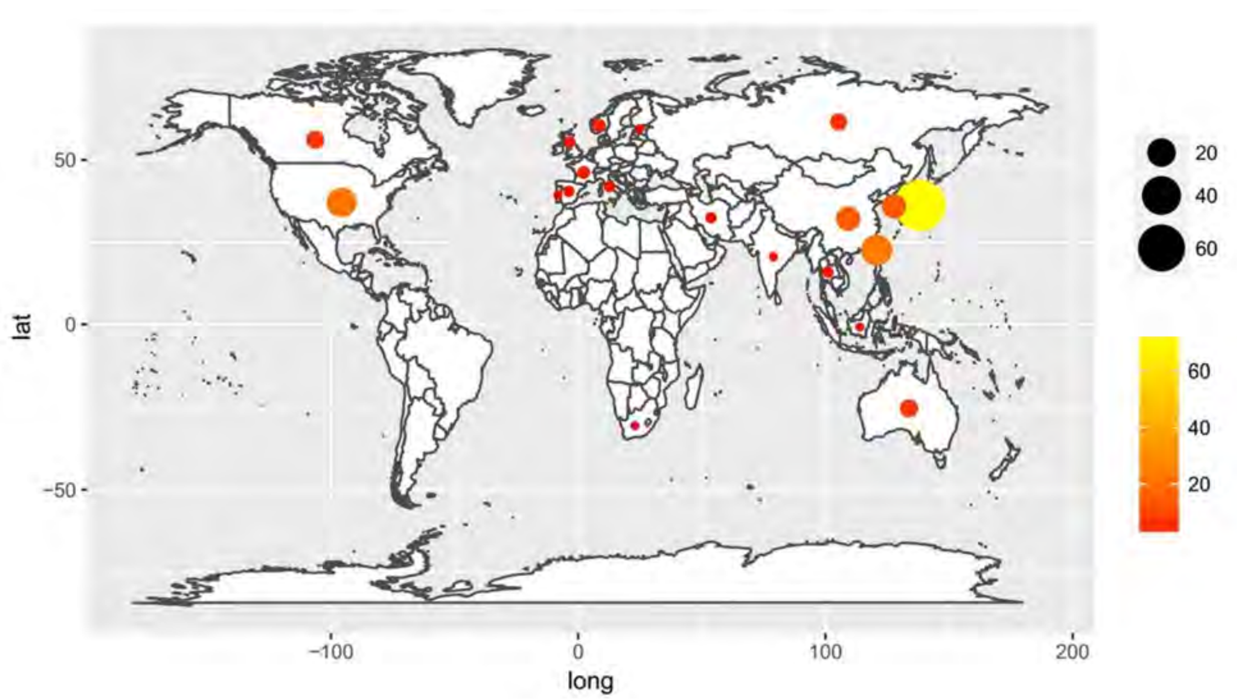


Figure 1. Number of marine species released. From Kitada (2018).

One of the primary weaknesses of stock enhancement initiatives to date has been the lack of evidence regarding their success. Why, then, have they been so popular and used by so many countries around the world? The early realization that marine fish populations were declining worldwide created concern that there may be insufficient food availability for a growing human population. Fish as essential food, especially in developing nations, plus the use of open access fishing, painted a dismal picture for the successful use of traditional fisheries management tools. Governments could, therefore, propose the use of stock enhancement as a simple solution, relying on donor funding and as a feel-good measure, while never really monitoring success or failure (Lorenzen et al., 2010; 2016).

Many scientists have challenged this method, and there is a range of existing peer-reviewed publications urging a more responsible approach (Blankenship and Leber, 1995; Leber, 2002; Lorenzen et al., 2010; Bell et al., 2008). While very few studies have evaluated the impact of enhancement, Kitada (2018) conducted a meta-analysis of the economic, ecological, and genetic impacts of marine stock enhancement and sea ranching worldwide. He found that most cases were economically unprofitable, that density-dependent growth caused by competition for food could be substantial, and growth rates could be reduced when the stock abundance was above carrying capacity. In 2020, Kitada focused on the 100 years of stock enhancement that had been conducted in Japan. He found all cases of Japanese releases, except for Japanese scallops, were economically unprofitable. In general, captive breeding was found to reduce the fitness of hatchery fish in the wild, while long-term releases reduced the genetic variation. He found that nursery habitat recovery and fishing pressure reduction produced better results in the long run.

# The theory behind stock enhancement

In theory, stock enhancement can increase yield through the manipulation of the population and/or food webs, aid in conservation and rebuilding of threatened and endangered populations, and provide partial mitigation for habitat loss and ecosystem effects of harvesting.

The premise of enhancement implies that there is some bottleneck in the natural world that limits production, and that if the animal can be raised past that critical period, they will survive and contribute to the biomass available for harvest. This bottleneck contributes to the carrying capacity of the environment, which is the ecological limit imposed by the natural environment to control abundance. Populations can only grow as large as the environment can support them, but releasing that bottleneck will ultimately create another. Many stock enhancement projects include habitat enhancement as a means of avoiding a habitat-driven bottleneck.

Bottlenecks show up as increased mortality or decreased growth at critical stages in the animal's life. Usually, this is due to a limitation of a critical resource such as appropriate habitat or food. This is a density-dependent process, so as abundance increases, so does mortality, or growth and reproduction may decrease. Compensatory processes can mask these effects but ultimately will affect the rate of population growth and carrying capacity. To effectively predict impacts, it is necessary to first have a deep understanding of the animal's life history and an understanding of the complex ecology of the ecosystem where stock will be released (Molony et al., 2003).

The candidates for stock enhancement should be chosen from among those species for which there is sufficient background information on population dynamic patterns, life histories, and habitat requirements, particularly for the focal lifecycle stages. For example, with a species where egg stages and larvae are density-independent, eggs contain the nutrition necessary for survival to the larval phase. Larval abundance is not controlled by predation, food limitations or disease; however, juvenile abundance is limited by predation, food availability, and/or disease.

Successful stock enhancement is possible for species with density-independent mortality in the larval or juvenile stage and for species with density-dependent mortality in those stages if the natural densities of larvae or juveniles are very low. These constraints may be bypassed by raising the animal beyond the stage of density-dependent mortality; additionally, the target stock must be one for which sufficient juvenile habitat is available in the area of the prospective release (Leber, 2002).

# The components of stock enhancement

## Production and nurturing of seed and juveniles

Ensuring both the quality and quantity of juvenile fish (fry) is an essential first component of stock enhancement (Sorgeloos, 1995). Early efforts often involved removing broodstock or larvae from the wild (Lavens and Sorgeloos, 1996). However, the stress on the larvae or perhaps their generalized weakened state from the capture process led to low laboratory survival, and the removal of a breeding adult was seen as a reduction in the wild production potential. This led to the "domestication" of broodstock, allowing for the completion of the entire lifecycle in a lab setting (Ikhwanuddin and Abol-Munafi, 2016).

Over the past 40 years, intensive larviculture has expanded into a multimillion-dollar industry (Sorgeloos, 1995). Seed production includes large-scale production of larvae through the breeding of mature adults, as well as the cultivation of prey and food for the prey, such as algae. In nature, the larvae of most fish and shellfish species eat small phytoplankton and zooplankton, and hatcheries try to find suitable food replacements that will provide a similar array of fat and proteins that the animals need to flourish. Early findings indicated that juveniles produced in the laboratory tend to be of poor health (physiological and morphological condition) with a low survival rate once released. These conclusions have led to increased demand for healthy and high-quality seeds, and shifted the focus of research and development of seedling production technology from quantitative expansion to quality improvement.

Larvae are best cultivated under controlled conditions. They are usually very small, fragile, and not physiologically developed to survive unattended. Many larvae have not yet developed a complete digestive system, perception organs (eyes, chemoreceptors, etc.), and have small mouths. A number of species (such as lobster and crab) also undergo metamorphosis at a certain stage, dramatically altering the nutritional requirements for growth and survival. Providing adequate nutrition for these sensitive larvae has become a major bottleneck which prevents full commercialization of some species.

The first food items usually required are phytoplankton (diatoms, flagellates, etc.) and zooplankton (copepods, cladocerans, decapod larvae, rotifers, ciliates, etc.). Raising these in culture requires a complex set-up that must be constantly monitored and maintained. Additional rearing of brine shrimp, *Artemia* sp., for live food is also often necessary, increasing feed and enhanced nutritional content. If available, processed food can be used when the shrimp is large enough. Depending on the species and culture technique applied, larval feed cost may account for up to 15 percent of the total production cost.

## Release into the wild

Large-scale enhancement projects will require pilot studies on release strategies (Lorenzen et al., 2010), the efficacy of which will affect the survival of hatchery animals in the wild (Svasand et al., 1990). In particular, the timing and method of release can be major factors in juvenile survival. Some of the key lessons learned from surveying the literature are summarized by Bell et al. (2008):

- Releases need to be made to avoid density-dependent mortality in the cultured animals or replacement of wild juveniles.
- Releases will be ineffective if the nursery habitat provides insufficient support.
- Survival of juveniles at one site does not guarantee survival at another site.
- Size at release affects economic efficiency and can vary by season.
- Predation is the greatest hurdle to the survival of released juveniles.
- Fitness of cultured animals may not be the same as fitness of wild stock.
- Added habitat with the addition of juveniles can increase the carrying capacity.

Lorenzen (2005) used North Sea sole data to simulate the impacts of release size on survival rates, finding that as the release size increased, survival increased. This is the major trade-off between enhancement success and economic feasibility: the longer you hold the animal, the more it costs, but the more likely it is to survive.

Rearing healthy animals in the lab has been accomplished with a number of species. However, juvenile behavior is an often-overlooked fitness component that is not evident until release. Hatchery-reared animals grow up in ideal conditions in the absence of predators or even competitors; they may not even be consuming their natural prey. These animals are often raised in tanks with no substrate or other characteristics of their natural environment, which could ultimately affect their morphology. For example, American lobsters raised in tanks without substrate do not develop the crusher claw (Goldstein and Tlusty, 2003). Identifying the factors and behaviors that are both similar and different between hatchery and wild animals is important for evaluating chances of survival. Davis et al. (2004) summarized studies showing higher mortality on released hatchery-raised fish species and invertebrates which could be caused by differences in swimming activity, reproductive behavior, habitat selection, feeding behavior, and levels of aggression.

Hatchery-reared animals may need extra time to acclimate to the release location, recover from the effects of the release method, or hide from predators. Changes in feeding and behavior often make the animal more susceptible to predation or movement away from the ideal habitat. Some release methods can improve the survival of hatchery releases and decrease the costs of stock enhancement (Taylor et al., 2017). Traditional release techniques include the direct release and the boat-based chute release. Most of these do not allow for bottom release and the animals therefore suffer higher predation rates (Zhang et al., 2021).

Predation is one of the most significant factors affecting the survival of hatchery-reared releases. Many studies evaluate the success of day or night releases or tidal cycles for improving survival by allowing for more acclimation time or more time for the juveniles to disperse and hide after release and before predators become active. For example, Daly et al. (2012) found predation on red king crab, *Paralithodes camtschaticus*, by fish to be higher during daylight hours. Castro et al. (2002) found a similar result for releases of American lobster, *Homarus americanus*, in Northeastern USA.

In addition to the time of release, another way to combat predation is by prolonging the time the animal is protected before it enters the natural environment on its own. Cage releases or other devices have been used to extend acclimation time. For example, an evaluation by Zhang et al. (2021) for two coral reef fish species indicated that cage releases have the potential to reduce the stress reaction for fish during the release process. PVC tubes were found to be most successful in releasing young abalone, *Haliotis asinina*, on reefs in the Philippines due to their stability in exposed wave environments (Lebata-Ramos et al., 2021).

## Quantitative assessments and tracking tools

One of the difficulties of working with unmarked animals is the natural variability of recruitment in the environment. Unless control areas are available for comparison, it is impossible to determine if survival rates vary naturally in the wild or if any increase is due to the addition of hatchery animals. The before-after-control-impact design is often used to look at impacts in the natural environment, controlling for before-after and control-impact. However, it requires intense and extended collection of data.

It was only in the 1980s that technical tools were developed to allow for the quantitative assessment of stock enhancement success using marked animals. Typically, visible markers such as morphological tags (fin clip, etc.), T-bar tags, and spaghetti and anchor tags (for use in fins and body) were suggested for short-term analysis where tag loss and mortality would be minimal. Animals did not have to be euthanized to locate or read the tag. They could be batch tagged (no individual numbers) or numbered to follow individual animals. Tag loss or behavioral change, or even higher predation rates, were concerns for longer-term studies. However, with many crustaceans there was high tag loss with molting. Some genetic tags and chemical tags were developed for large numbers of releases. Otolith marking using heat, drying, or chemicals requires dissection of the animal after capture.

Internal tags (microwire, passive integrated transponder, and internal elastomer tags) could be batched or numbered but require detection equipment and usually the animal must be dissected to obtain the information. Acoustic tags, such as radio tags, data storage tags, global positioning system (GPS) fish tags, and GPS sonar may have active transmitters. Acoustic tags, if monitored frequently, can be used to distinguish behavioral differences between hatchery and wild populations (Taylor et al., 2017). The cost of tags, monitoring, and recovery can be considerable, as can efforts to follow recaptures for any prolonged period.

In addition to field trials, models can simulate potential results. In the highly variable marine environment, it is important to look beyond just the species requirements and introduce ecosystem parameters as factors of success. Quantitative tools, such as ecosystem modeling, can be applied to determine probable outcomes under varying conditions (Taylor et al., 2017). For example, physiological models have been combined with estimates of resource availability to evaluate the release densities for the flatfish, *Paralichthys olivaceus*, with varying levels of prey availability (Yamashita et al., 2017). Stochastic, environmentally induced variations in spawning success can lead to poor reproductive outcomes for wild and hatchery-reared animals (Kawabe et al., 2017). The importance of understanding animal density and carrying capacity should not be ignored (Taylor et al., 2017). These models are a good first step in designing pilot field trials and identifying possible outcomes.

# Goals of stock enhancement

To measure the success of a stock enhancement initiative, objectives need to be clearly stated and agreed upon (Gislason et al., 2000). Strong biological or ecological metrics should be quantifiable, such as changes in spawning stock biomass, fishing mortality, or fishing effort (Camp et al., 2014), which requires careful experimental design.

The use of socioeconomic objectives alongside environmental goals can be a powerful driver for developing and maintaining sustainable fisheries (Radomski et al., 2001; Cowx and van Anrooy, 2010), although criteria for success will vary by stakeholder. In reality, judgment of overall project success is often "personal" – a complex function of ecological, economic, philanthropic, political, sociological, and perhaps even religious factors (Hilborn, 1998). Economic cost is a more subtle success criteria. For example, Moksness (1998) points out that salmon ranching in Norway is unlikely to be profitable and requires government subsidy; however, this subsidy is regarded as funding well spent for various political reasons.

## Biological and ecological considerations

One of the primary purposes of stock enhancement is to increase population size or growth without harming wild stock. The release of fish is expected to increase the number of animals surviving and becoming available to the fisheries, especially during years with poor supply of juveniles in the nursery grounds. This practice implies that the recruitment bottleneck occurs prior to the nursery life stage, and that there is ample prey and few predators during the juvenile stage. While considerations will vary, for most projects the major biological objectives include:

- Increased abundance of juveniles or adults
- Increased abundance of spawning stock
- Re-population of an area with low abundance

Restocking can be applied to stocks that are chronically suffering from poor recruitment and where the spawning stock biomass is well below the safe biological limit set for that stock. In such cases, stock recovery is urgent (Støttrup and Sparrevohn, 2007). Stock enhancement can also be employed to even out natural fluctuations in recruitment, thereby stabilizing the fisheries.

As previously mentioned, adding animals to a density-dependent system can disrupt major ecological relationships and change the genetic composition of the stock. For example, for a population that is below carrying capacity and therefore less affected by density-dependent effects, the release of hatchery-reared animals should not negatively affect the wild stock (Deng and Ren, 1994; Ye, 2000; Ye et al., 2005). However, for a stock that is close to or at carrying capacity, the addition of hatchery-reared animals may result in stock replacement instead of stock enhancement because of a resulting increase in density-dependent mortality (Hilborn, 1998; Ye et al., 2005). Therefore, it is important to consider the ecological components of the system. While components will vary, for most projects, ecological objectives include:

- No disruptions to the ecological community (wildness of the species, prey, or predator)
- No reduction in biological diversity
- No reduction in fitness of individual species
- Augmented nesting sites (i.e., sea turtles)

Ecological and genetic impacts are of global concern, yet there is a paucity of research conducted in these areas (Kitada, 2018). In one of the few reports available, Kitada (2018) examined extensive data sets for the Pacific salmon release program by looking at catch rates from 1925 to 2016 and release statistics from 1952 to 2016. A significant increase in the total catch of pink, chum, and sockeye salmon since the 1970s was correlated with releases; however, a significant decrease was seen in coho and Chinook salmon since the mid-1990s. He further examined the life history patterns of these species and concluded that interspecies competition was occurring between chum and pink salmon for similar food, resulting in reduced growth of wild and hatchery-reared animals. Kitada (2018) also reviewed the literature for studies that reported genetic effects of hatchery releases and found evidence for genetic effects on stocked populations in 11 of 28 cases; 13 showed no effects.

More recently, new molecular techniques (omics) have become available to identify, characterize, and quantify biological systems. They are being applied to understanding the complex interactions between genotypes and phenotypes, and between the host, microorganisms, and the surrounding environment (Nguyen and Alfaro, 2022).

## Determining economic value

The economic outcomes of an enhancement project can be one of the most challenging variables to calculate. Often, pilot-scale research project costs do not consider a viable business model. Instead, they rely on volunteer labor (i.e., students or others) and external funding sources, and fail to plan for future changes in supply and demand or shifting market prices. In 1998, Hilborn reviewed the economic performance of nine marine stock enhancement projects for fish, turtles, and lobsters that involved restocking. None of the projects showed clear evidence of increased abundance, and none could be evaluated for economic results.

For successful scaling to occur, projects should include a bioeconomic analysis specific to the location. This is especially crucial for benthic species with marked spatial variations in carrying capacity, recruitment, and growth and mortality rates, which constitute input variables affecting the economic analysis of stock enhancement. Moreover, some economic inputs might differ on a regional scale (e.g., opportunity costs of labor and capital).

A marketing analysis is also required to inform the choice of the species to be enhanced based on current supply and demand. Different product types (whole weight, muscle weight) and the corresponding unit prices should also be included in the economic analysis, according to variations in local/international demand. Economic projections should be employed to estimate the net present value of the enhancement activity; abundance, growth, and survival estimates derived from the short-term project must be extrapolated to the period at which organisms will be available for harvesting.

The economic benefits of the program must be compared with the costs, in addition to any economic externalities such as environmental impacts. While implementers account for most of the upfront expenses involved with running hatcheries, there is often a lack of additional funding to cover long-term activities that would contribute to programmatic longevity, regular programmatic evaluations, and – where necessary – corresponding changes in management practices. Finally, any economic evaluation must include the cost of harvest. The overall economics of stocking should be compared with that of proven alternatives such as habitat protection, fishery regulation, and stricter enforcement (Hilborn, 1998). Once the net increase in catch is determined, an economic value can be determined, which will depend on the extent to which any increases in production affect price.

Numerous pilots have demonstrated that the most successful enhancement initiatives are those that generate additional benefits such as job creation, access to new markets (domestic and international), maintenance of current markets, increased income through ecolabels or certification, or access to community funds. Pinkerton (1994), for example, describes the economic benefits of Alaskan salmon enhancements for the Prince William Sound Aquaculture Association, who received an eight-year period of price advantage for the association's cost recovery due to improved quality, greater volume, and catch stabilization. Enhancements have the potential to make economic and social benefits from aquaculture technologies available to stakeholders such as traditional fishermen (Lorenzen et al., 2016).

The demand for and value of many seafood products continue to rise, and overall fish prices have followed an upward trend due to limitations on supply growth combined with increasing consumption numbers. In nominal terms, prices in the fishery and aquaculture sector will continue to increase over time, as will the percentage of fish production destined for human consumption, which is expected to reach 89 percent by 2020 (FAO, 2020). The drivers behind this increase will likely be a combination of high demand resulting from rising incomes and urbanization motivating the rapid expansion of fish production, improvements in post-harvest methods, and investment in different distribution channels to expand commercialization opportunities. Market demand will also be stimulated by changes in dietary trends as consumers look for increased variety with an increased focus on improved health, nutrition, and diet, and global fish consumption in 2030 is projected to be 18 percent (28 million metric tons live weight equivalent) higher than in 2018. Estimated demand shifts and supply scenarios (which account for policy reform and technology improvements) indicate that edible food from the sea could increase by 21 to 44 million metric tons by 2050, an increase of between 36 and 74 percent compared to current yields. This represents 12 to 25 percent of the estimated increase in all animal protein needed to feed 9.8 billion people by 2050 (Costello et al., 2020).

## Social and cultural aspects of fisheries management

Integrating place-based social and cultural aspects of fisheries management into management plans is just as critical as meeting biological and economic objectives. Even if fish production rates are improved through stock enhancement efforts, this does not automatically ensure any additional benefits for fishermen or the wider fishing community. To develop and maintain positive relationships between fisheries resource users and managers – leading to appropriate and accepted management approaches – it is fundamentally important to understand the beliefs and attitudes of users regarding particular management approaches (Obregón et al., 2020).

Stock enhancement is seen as a method for sustaining both fishing effort and stocks; however, it can involve trade-offs between negative economic impacts and catch-related benefits for fishermen. To assure project success past the pilot phase, it is essential to view the approach through fishermen's eyes (Taiarui et al., 2019), ensuring that they can benefit from the management changes enacted, and preferably participate in their creation.

Ultimately, the efficacy and success of management plans depends on buy-in from the fishermen, who are the true resource stewards. Creating social and economic benefits linked to management requirements while simultaneously acknowledging and integrating local ecological knowledge will likely greatly improve management outcomes. There are a range of benefits or assumed benefits recorded for stock enhancement that result in both economic and social benefits for fishermen, including new opportunities for fisheries-related livelihoods and increased opportunities for involvement in the management and governance of the resource (Lorenzen, 2008; Smith et al., 2005; Garaway, 2006).

Lorenzen (2008) developed a framework for analyzing aquaculture-based enhancement fisheries systems with an overall structure that includes outcomes, patterns of interaction, and situational variables (Figure 2). This framework is based on core ideas of Institutional Analysis and Development (IAD) proposed by Ostrom (1992). As illustrated, outcomes are influenced through two pathways: physical-biological processes and the action of stakeholders. This framework has been applied to fisheries enhancement systems by Lorenzen et al. (1998).

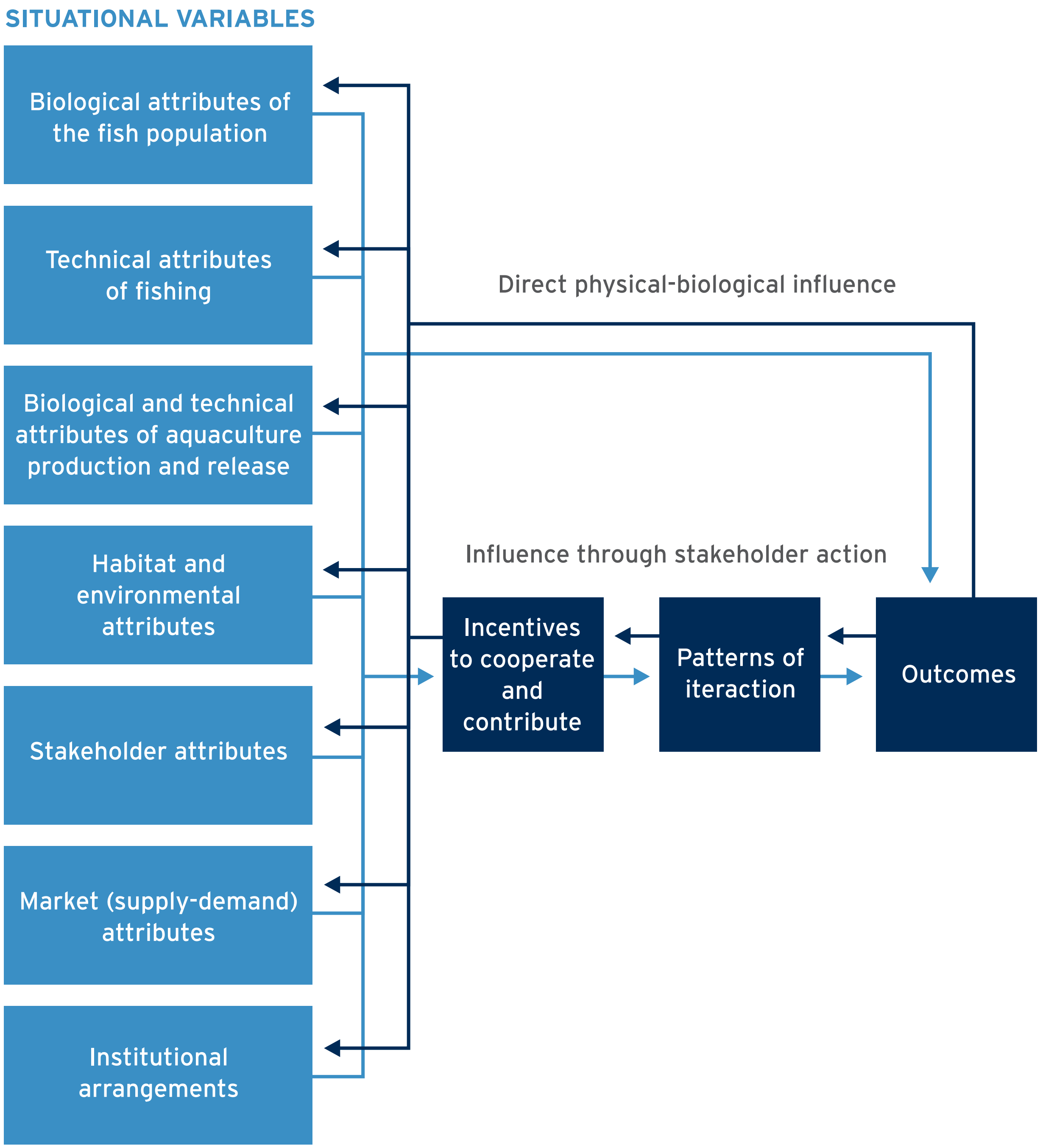


Figure 2. Framework for analysis. From Lorenzen (2008).

In addition, Lorenzen (2008) also created a process for developing enhancement for fisheries systems. He suggests that successful enhancement initiatives involve technical innovation, in addition to "leaps of faith". They should also be stakeholder driven and include all key stakeholders. He outlines five important steps (Figure 3).

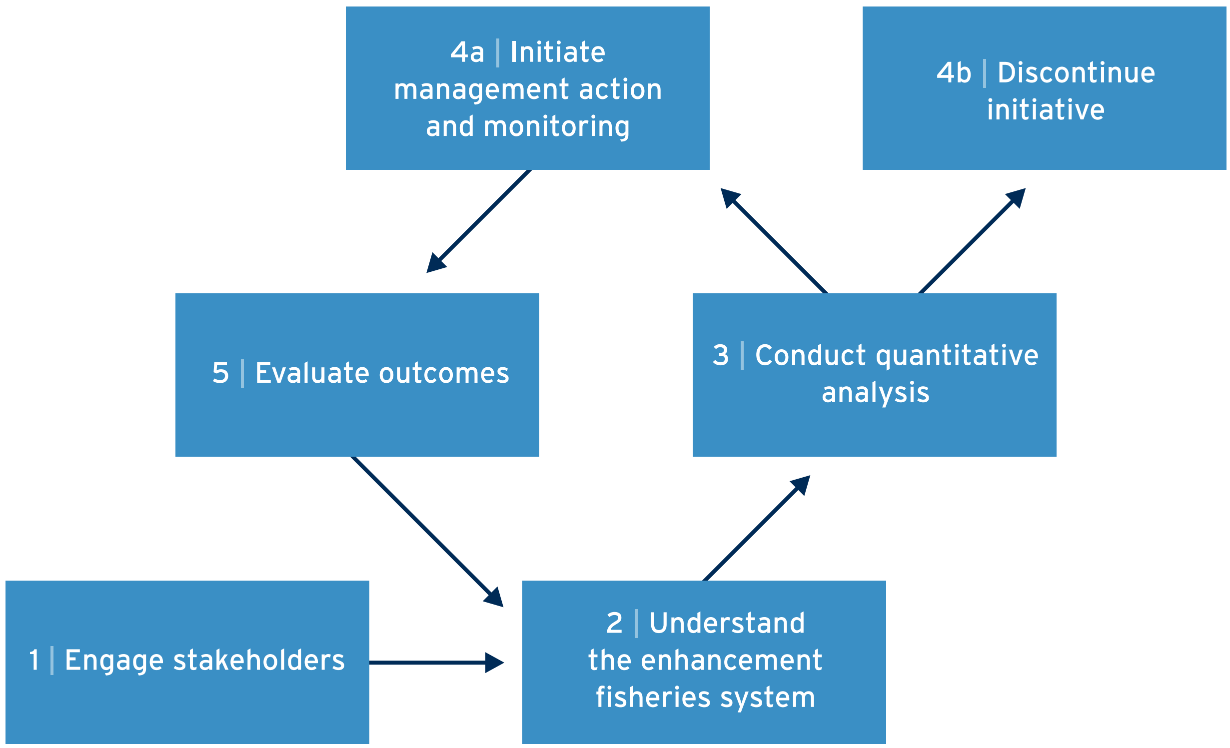


Figure 3. Process for developing enhancement systems. From Lorenzen (2008).

The first key step is the engagement of stakeholders. Those directly involved in the supply chain should be the ones to make development and management decisions. Given that the actions of stakeholders not only drive enhancement developments but are based on perceptions of resource status, it is important to ensure that perceptions reflect the true state of the resource. Since stock enhancement is applied to a common pool resource, issues involving ownership rights, control, and use are complex and difficult to control and predict. Therefore, the thinking needs to go beyond the traditional technical research and include social science approaches, as understanding how human interaction affects the system and the biological outcomes is important in this scenario.

In one example, Garaway et al. (2006) highlighted lessons learned through stock enhancement in Lao People's Democratic Republic (PDR), utilizing qualitative and quantitative methods to gain an understanding of how and when enhancement would be accepted by resource users. In southern Lao PDR, enhancement through stocking has been promoted, but uptake and management were affected by a range of factors. Garaway (1999) studied 31 villages and waterbodies and found that "villages were more likely to take up and manage enhancement when they could actively see for themselves, prior to implementation, the benefits of doing so" (Garaway, 2006). Factors that contributed to their commitment included learning firsthand from other villages and the presence of key individuals in their village. Most important was the idea that the user community and its characteristics impacted how they chose to manage the resource, which in turn affected whether an increase in production would increase yield. Resource users were considered drivers of the enhancement process and not just recipients (Garaway et al., 2006). Using the IAD framework (explained on page 14), the researchers were able to conceptualize interactions and establish a common understanding of the systems based on local knowledge in addition to technical and scientific knowledge.

# Stock enhancement as a management tool

Molony et al. (2003) proposed a rigorous flow chart for decision making, justifying the complexity as necessary and well-balanced. The flow chart describes a four-step process: a comprehensive review of the species and ecosystems as well as fisheries and management targets; a comparison of all management tools with the potential to meet management targets; a scientifically based pilot project with clear objectives, targets, and evaluation; and a full-scale enhancement program if pilot meets the objectives (Figure 4). This approach incorporates the enhancement into the much larger governance and management system and involves all aspects of management, including biological, ecological, social, and economic.

Lorenzen (2014), in turn, proposed that fishing effort controls, habitat enhancement, and stock enhancement are the three principal ways that fisheries can be sustained over time; believing that stock enhancement should not be viewed alone, but rather in combination with other management strategies. Hart et al. (2013) suggested using a combined effort reduction/enhancement approach for abalone in Australia. Ironically, enhancement is often proposed as an alternative to effort restrictions rather than as a complementary management technique.

Effective enhancement is often combined with habitat improvement and repair. Zhang et al. (2014) added the construction of artificial oyster reefs to support sea cucumbers in China, resulting in higher-than-normal densities. Wu et al. (2016) used an Ecopath model to evaluate the effects of kelp culture and artificial reefs on enhancement activities of sea cucumber, *Apostichopus japonicus*; abalone, *Haliotis discus hannai*; and Japanese flounder, *Paralichthys olivaceus*, in the Yellow Sea. The ecosystem was dominated by benthic production, and simulation results suggest that kelp culture provides a significant subsidy to the benthic detritus, thereby favoring stock enhancement for benthic species in the region. By contrast, the simulation of removal of all kelp farms over 10 years resulted in a twofold increase in the relative biomass of type III fishes (fishes found in the water column above the artificial reefs, e.g., *Scomberomorus niphonius*) and a 120 percent increase in their main prey, small pelagic fish, while the biomass of sea cucumber decreased by 31.4 percent.

Kitada (2018) evaluated the combined effects of enhancement, habitat restoration, and effort reduction on the success of the major red sea bream enhancement program in Kagoshima Bay, Japan. Results showed that increased seaweed nursery grounds combined with reduced fishing efforts were the primary factors associated with wild population recovery. Although with low wild populations, genetic diversity was initially affected by hatchery-released animals, this became less of an issue as the wild stocks recovered. The conclusion was that enhancement cannot be successful over the long term unless sufficient efforts are also made to reduce harvest rates and rehabilitate natural habitats.

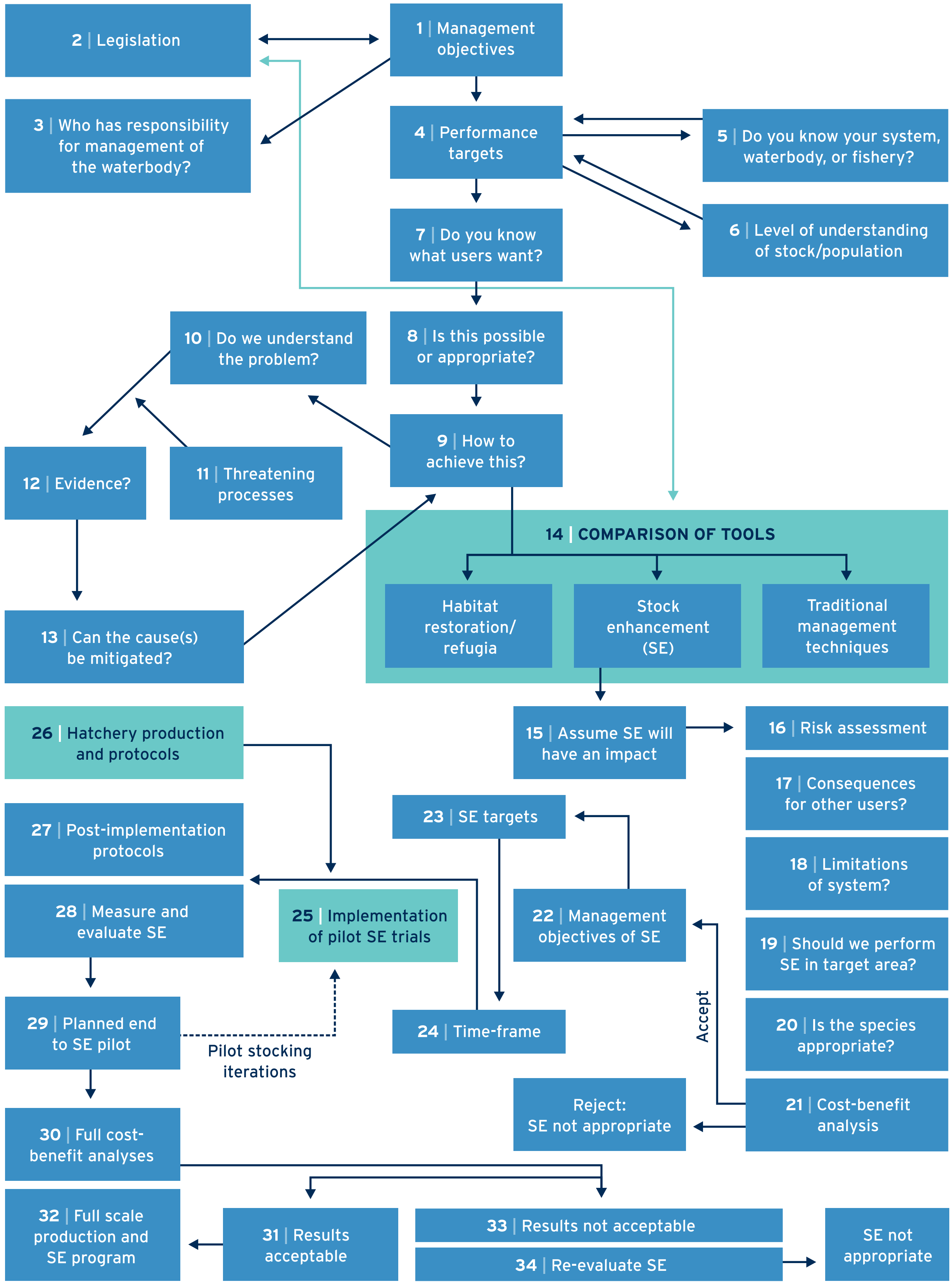


Figure 4. Proposed flow chart for decision making. From Molony et al. (2003).

While understanding changes in fish populations, species composition, and ecosystem conditions is critical to making informed decisions, effective fishery management includes both strategy and tools. These tools may be designed and applied to regulate several aspects of a fishery, including species composition, catch per unit effort (CPUE) of fishing, spatial patterns of harvesting, and single or multiple species populations. In general, two major categories of management tools are used to limit harvest: input controls and output controls. Input controls are regulations directed at controlling the fishing power and total effort used to harvest fish. Output controls are direct limits on the number or size of fish harvested regardless of the inputs used – tools that directly restrict catch.

Various population models can be used to compare the potential effectiveness of a plan once performance criteria are established. Life tables and deterministic matrix models allow for a multitude of "what if" scenarios. Sensitivity analysis may be applied to study how these various sources of uncertainty within the model contribute to uncertainty of the model as a whole. For example, enhancement can be incorporated by changing the survival rates of some proportion of eggs and larvae. Models can be used to explore the potential impacts of interactions between hatchery and wild animals, such as increased cannibalism or competition. Population level effects of improving habitat, decreasing harvest pressure, and enhancement can all be compared using analytical or iterative models. Since cost effectiveness is a common hurdle for enhancement, all management tools should be considered, including combinations that can be applied in tandem to reach the agreed objectives more efficiently and rapidly.

# Stock enhancement and other innovative approaches for crab

Coastal invertebrates may have a higher potential for effective stock enhancement success because of their fixed or sedentary characteristics and a higher likelihood of creating self-replenishing populations within a relatively localized region (Bell et al., 2006; Gomez and Mingoa-Licuanan, 2006). Stock enhancement has also been suggested for a larger range of invertebrates and vertebrates, both sessile and motile species in several countries.[1]

## Portunid crabs

Portunids are distinguished from other brachyuran crabs by paddle-like structures (propodus and dactylus) on the fourth set of pleopods. These structures give portunid crabs some of the strongest swimming abilities of any invertebrate and are responsible for the popular names of "swimmer" and "swimming" crabs (Poore, 2004; Hartnoll, 1971), the source of the most expensive "lump fin" meat product. Portunids are captured in large numbers in both marine and estuarine waters in tropical and

[1] International Crustacean Task Force. In November 2020, The Lenfest Ocean Program supported the formation of an expert task force led by Dr. Kristin Kleisner, Environmental Defense Fund, and Dr. Yong Chen, University of Maine. Both Dr. Kleisner and Dr. Chen have global expertise and in-depth knowledge about crustacean fisheries in four case study countries – China, Indonesia, the Philippines, and the United States. Through cross-cultural and interdisciplinary collaboration, the team will develop guidance on scientific and management approaches for these fisheries that considers the unique life histories of crustacean species and spans a spectrum of research needs, data availability, and resource capacity settings. The following webinar was produced by the Task Force in 2022 to inform of progress on stock enhancement for crustaceans in several countries: https://www.youtube.com/watch?v=CvFdCp-sIiE

temperate regions globally (Poore, 2004; Johnston et al., 2014; López-Martínez et al., 2014; Chesapeake Bay Stock Assessment Committee, 2016), although landings are greatest in the Indo-West Pacific because of the abundance of *Portunus trituberculatus* and *Portunus pelagicus* (Tweedley et al., 2017).

Portunid crabs typically complete part of their lifecycle in shallow water (Johnston et al., 2011). Most species experience habitat shifts throughout their development stages, which could result in migratory behavior. Any enhancement strategies need to account for these complex lifecycles in terms of release strategies and overall objectives, especially if the animals travel between countries or areas with diverse management strategies in place (Hines et al., 2008). The lifecycle of the blue swimming crab (BSC) involves many different habitats, and enhancement impacts may be affected by where and when crabs are released. In most portunid species, spawning takes place in shallow coastal waters during summer, with offshore winds at night and onshore winds during the day (Forward et al., 1997). After hatching, zoea are transported to offshore waters by migrating vertically in the water column to the surface at night (McConaugha et al., 1983). Flood tide transport facilitates settlement in coastal and estuarine waters for *Callinectes sapidus* and other estuarine crab species. This is a form of selective tidal-stream transport which enables megalopae to remain in the water column during flood tides and shelter during ebb tides.

Juveniles select habitats that enhance survival rather than growth and show internal and external morphological changes, e.g., the abdominal flap of females widens and becomes loose after the pubertal molt, while the relative size of male chelipeds (claws) increases. Mating takes place between hard-shell males and soft-shell females prior to the transport of eggs from the ovary through the spermatophore and onto the abdominal pleopods. The hard-shelled male protects the soft-shelled female until her carapace has hardened (Hartnoll, 1969; Kangas, 2000). Females of some species then migrate offshore out of mangrove systems, e.g., *Scylla serrata* (Hyland et al., 1984), or near-shore coastal waters, e.g., *Portunus sanguinolentus* (Sumpton et al., 1989), to release their eggs. In contrast, others migrate from estuaries to marine waters, e.g., *Portunus armatus* (Potter and de Lestang, 2000) and *Callinectes sapidus* (Turner et al., 2003; Aguilar et al., 2005), respectively. Other species appear to mate and release their eggs where they live and do not migrate during reproduction (Safaie et al., 2013; Zairion et al., 2015).

Species inhabiting temperate estuary waters commonly show seasonal patterns of abundance, typically in regions where the water bodies exhibit larger fluctuations in temperature and salinity. As a result of this migration, coastal populations, particularly those near estuary mouths, exhibit a pattern of abundance that is opposite to that observed in the estuary, with crab abundance peaking in late winter. This pattern is not seen in *Callinectes sapidus* in Chesapeake Bay, as they also live in low salinity estuaries (Posey et al., 2005; Ralph and Lipcius, 2014). Crabs in this group prefer warm, shallow waters in summer, but relocate to deeper areas that cool more slowly in winter (Wrona, 2004; Kaufman, 2014). Similarly, an increase in the abundance of *Portunus armatus* in deep waters of a coastal embayment in Southwest Australia (Cockburn Sound) from July to September (winter) is considered to be related to a shift away from the lower temperatures in the embayment's shallow waters (Potter et al., 2001).

## Enhancement programs

There have been a number of release programs designed to increase portunid crab stocks, these include gazami crab, *Portunus trituberculatus*, in Japan; blue crab, *Portunus pelagicus*, in Thailand; mud crab, *Scylla paramamosain*, in Japan; mud crab, *Scylla* spp., in the Philippines, and blue crab, *Callinectes sapidus*, in the United States. Unlike the growing stability seen in catch rates of world finfish fisheries, global catches of portunid crabs continue to increase as demand grows. In addition to overfishing, existing portunid fisheries are under additional pressure because of environmentally induced variations in recruitment (Lipcius and Stockhausen, 2002; Johnston et al., 2011), leading to population collapses (as reported in Tweedley et al., 2017).

### Blue swimming crab, *Portunus pelagicus*, the Philippines

The Danajon Bank reef areas were stocked with hatchery-bred BSC produced from the BFAR 7 hatchery facility in Sinandigan, Ubay, Bohol. A total of 1,202,439 individual C4 BSC and 227,301 crablets were dispersed. Asynchronous stocking of hatchery-bred BSC in Danajon was carried out between December 2017 and December 2020. In addition, catch monitoring was carried out from June 2019 to September 2020, and the hatchery-bred BSC were dispersed to areas where the BSC is naturally occurring. The stock assessment was purposely conducted to monitor the impact of BSC stock enhancement activity relative to the biological status of BSC in the dispersal areas (Abrenica et al., 2021). Compared to the BSC fishery in the Visayan Sea, the spawning potential ratio was higher than 21 percent for the same period. The higher spawning potential ratio in the Danajon Bank compared to the Visayan Sea may be credited to the effect of stock enhancement activity implemented in the area, though observation is not yet conclusive.

To continue the BSC stock enhancement activity, it was recommended that the following strategies for improvement of the project should be taken into consideration: 1. Characterization of BSC dispersal sites/areas should be conducted before stock enhancement and/or dispersal activity. 2. The survival rate of BSC should be determined before dispersal; this can be accomplished by first holding the hatchery-produced juvenile BSC in the hapa nets for three to seven days to monitor survival before release. 3. Hatchery-bred BSC should be tagged for monitoring and evaluation purposes.

### Blue swimming crab, *Portunus pelagicus*, Thailand

Between 2001 and 2011, catches of crab in Thailand declined by 43 percent. Pilot-scale restoration efforts (Nitiratsuwan, 2013) were conducted in a small area in Trang Province, Thailand, where 30,000 crablets were released. While the catches were shown to have increased in traps in 2013, the study did not consider changes in natural production, and the released crabs were unmarked.

A different approach was used in Prachuap Khiri Khan Province (Arkronrat et al., 2013) where a "crab bank" was developed. Berried *Portunus pelagicus* were captured and held in sea cages or in the hatchery until they spawned. Females in sea cages were released, but females at the hatchery were sold at market and 50 percent of the sale was reinvested in the hatchery. Of the fishermen surveyed one year after implementation, 60 percent reported increased catches. Similarly, a crab bank program in Banton Bay Thailand was recently evaluated using an Ecopath model. Results showed a significant increase in biomass of BSC after 10 years of stocking program in Bandon Bay, the Gulf of Thailand. The results of the Ecopath model revealed higher maturity and stability after 10 years of the BSC stocking program. The mixed trophic impact indicated bottom-up regulation and that the increase of BSC negatively impacted only mantis shrimp (Sawusdee et al., 2022).

## Blue swimming crab, *Portunus pelagicus*, Western Australia

Research-based work was done to determine if the BSC would be a good candidate for stock enhancement (Jenkins et al., 2017). Successful hatchery rearing and a small release was carried out in the Peel-Harvey Estuary. The recommendation was to continue to develop hatchery technology to reduce costs and increase survival.

## Mud crab, *Scylla* spp., the Philippines

Four species of mud crab, *Scylla* spp., are found in shallow soft-sediment habitats in the tropics and represent an important source of income for many coastal communities (Le Vay et al., 2001). These stocks have experienced overfishing due to various issues, including poor or non-existent management measures. It was found that animals do not move far after being released. Both *Scylla paramamosain* and *S. olivacea* have fast growth rates, reaching maturity in only five months. Small home ranges and fast growth are both positive characteristics for enhancement species. Lebata et al. (2009) tested size release survival and found the percentage survival increased from 0 percent at 20 to 25 mm, to 47 percent at 50 to 55 mm. Between May 2004 and September 2005, 5,273 individuals were released and a corresponding increase in CPUE was reported as 51 percent in number and 42 percent in biomass (Lebata et al., 2009).

However, despite the apparent success of the enhancement, refinement of the larviculture technology is required to increase efficiency and make the program economically viable (Le Vay et al., 2008). Limitations in habitat availability due to mangrove destruction may also hinder the success of this program in the future.

## Mud crab, *Scylla paramamosain*, Japan

A pilot study was conducted from 1997 to 2002, where between 72,000 and 149,000 *Scylla paramamosain* were released into a small embayment, Urado Bay, Kochi Prefecture, Japan. They were tagged using a genetic marker developed by Obata et al. (2006). Recapture rates were ultimately low, ranging from 0.24 percent to 1.7 percent. However, because these species grow to such a large size and have a high ratio of price landed compared to the cost per hatchery-reared juvenile, stocking was shown to be economically viable (Obata et al., 2006; Hamasaki and Kitada, 2008). From 2000 to 2004, between 285,000 and 1,026,000 *Scylla paramamosain* and up to 173,000 *S. serrata* were released throughout Japan (Hamasaki and Kitada, 2008).

## Gazami, *Portunus trituberculatus*, Japan

*Portunus trituberculatus* was one of the first species to be considered for stock enhancement in 1963 after many fisheries experienced significant declines in abundance (Secor et al., 2002). The number of juveniles released increased rapidly from 6.3 million in 1977 to more than 30 million in 1986, remaining constant thereafter (Hamasaki et al., 2011). In 2017, 14 hatcheries were involved in the seed production. Mass mortalities are known to occur during the zoeal and megalopa stages and during metamorphosis caused by disease and molting death.

Significant positive relationships between the number of juveniles released and the minimum values of catches were detected for Hamana Sea, Seto Inland Sea, Central Pacific, and Western Sea of Japan (Hamasaki et al., 2011). This result has been questioned by Hines and Zohar (2018). A small tag release experiment with release in two small bays was conducted to gain more clarity. They indicated a 1.5 percent contribution to the catch. Economic efficiency values indicated that for some of the release programs the economic benefits would cover the costs of juvenile production and release. Hamasaki et al. (2011) evaluated the program's influence at the national level in Japan and concluded that the release programs at the megalopa C2 stage or greater had sustained fishery production, indicating that size at release affected their overall contribution to the catch. They concluded that holding an animal past C2 was too expensive, and mortality increased markedly (Hines and Zohar, 2018). There is some confusion over the interpretation of the results (Hines and Zohar, 2018). Re-examining the data does not show the same results with correlations, and how they reached the conclusion of an individual weight of 33.6 g per release was unclear. However, the small pilot study confirmed that many hatchery-raised tagged animals were found in the markets.

### Gazami crab, *Portunus trituberculatus*, China

Early studies concluded that hatchery releases were present in 60 percent of the landings; however, the animals were not tagged (Xie et al., 2014). In 2014, Xu et al. (2018) released almost 2 million untagged hatchery-raised juveniles. Using biological surveys, they found that the density and spatial distribution of crabs had increased. They calculated future biomass and economic benefits of the release, but the methods were unclear. Cai et al. (2019) developed a genetic marker that was tested at 10 hatcheries in Shandong Province; in this instance, only 14.81 percent of recaptured crabs were identified as hatchery-reared.

Additional information and case studies regarding clawed and spiny lobsters and non-portunid crabs can be found in Annex II.

# Applications for Southeast Asia

Many crab stocks in Southeast Asia have been subject to decades of overfishing combined with a lack of effective fisheries management (Hines and Zohar, 2018). Even in areas with substantial management plans in place, non-compliance levels among fishermen can be high, especially when driven by consumer demand and livelihood needs. In Indonesia, Saputra (2020) found that when the abundance of legal-sized swimming crabs was low, the products were expanded to include processing that could be applied to crabs of all sizes. Indonesian law prohibits the fishing of egg-bearing or juvenile crustaceans. However, Farhan et al. (2018) found that fishermen continue harvesting all invertebrates purchased by either the local processing crab mini-plants or intermediaries for the Vietnamese lobster farms and American seafood markets (Petrossian and Clarke, 2019). Buyers often use financial pressure to continue this practice through loans to the fishermen that must be repaid in product, locking fishermen into long-term debt cycles. The fishermen have no incentive to follow the rules, and the extreme economic and social situation makes it impossible for them to comply. The failure of this management regime illustrates the lack of understanding of the fisheries system and the need to connect the fishing, processing, and selling sectors.

One of the positive aspects of marine stock enhancement is that it can influence stakeholder behaviors and beliefs regarding fisheries management. A study on inland stock enhancement in Lao PDR conducted by Garaway (1999) showed that 65 percent of villages created and maintained management bodies. These management bodies created new rules and regulations either on their own or in collaboration with the government fisheries departments to help manage the resources.

In these areas of the world where traditional management practices are ineffective and/or lacking, stock enhancement is often perceived as an immediate solution for the recovery of declining stocks (Grimes, 1998; Borg, 2004; Molony et al., 2003). Over the past 20 years, many Southeast Asian countries have identified stock enhancement as a potential management strategy to help reestablish depleted resources rapidly, attempting this “quick fix” rather than implementing or enforcing far more complex fisheries management reforms. Hines and Zohar (2018) submitted a review of some approaches for stock assessment of the swimming crab, *Portunus pelagicus* in the Philippines. As the Philippines is considering new comprehensive management measures for the BSC fishery, it is attractive to consider an enhancement program to complement stricter management measures. The BSC has characteristics that make it attractive for enhancement. It has tremendous reproductive potential, the hatchery technique is well established, and potential release sizes have been determined. Once released, the BSC grows quickly, readily adapts to the wild conditions, and can recruit into the fishery in six months.

Since many areas have depleted populations, a restocking program could help restore a reproducing population if combined with other management measures. Other areas with more abundant crabs could be evaluated for recruitment limitations and possible augmentation of critical habitat.

Specific suggestions include:

- Considering a restocking experiment into carefully chosen sites where they can grow to reproduce rather than an enhancement project. The goal would be to increase the number of reproducing females.
- Determining appropriate release size. Aim for release after the crab has reached the size where sedentary behavior has replaced dispersal behavior (This is about 2 cm – C7 for blue crab or C4–C5 for gazami). More behavioral research should be conducted.
- Implementing stricter management regulations for the hatchery-released animals. For example, larger minimum size and restrictions on harvesting berried females.
- Choosing sites carefully.
- Tagging all released crabs (microwire or DNA fingerprinting).

Some negative effects of enhancement need to be avoided, such as disruption of the ecosystem or competition with wild stocks. One of the points of emphasis made by Molony et al. (2003) was the importance of ecosystem-based fisheries management (EBFM). The concept of EBFM is to "manage fisheries in a manner that addresses multiple needs and desires of society, without jeopardizing options for future generations, to benefit from the full range of goods and services provided by marine ecosystems" (FAO, 2003). To have successful EBFM, management authorities must have the ability to control and report landings, decrease overfishing, reduce bycatch, and account for any other impacts on fisheries within the larger ecosystem (Christie et al., 2007). Although many Southeast Asian countries lack these prerequisites, much can be done in the form of ecosystem "reasoning" to modify fishery management systems that have a large amount of uncertainty. For example, one option often used within data-deficient and small-scale fisheries is the use of local or traditional ecological knowledge (Johannes et al., 2000).

Lastly, a major point that Molony et al. (2003) provided is that for stock enhancement to be effective, it must be performed in congruence with other fisheries management tools.

# Annex I: Global case studies

## Blue crab, *Callinectes sapidus*, USA

In the early 2000s, stakeholders in the Chesapeake Bay blue crab fishery suggested using hatching and rearing technologies and the release of juvenile crabs in response to a decline in Chesapeake blue crab landings; in response, an experimental blue crab enhancement program was initiated in 2002 through a multidisciplinary and multi-institutional program. Over five years, approximately 300,000 crabs were cultured, tagged, and released into the Chesapeake Bay nursery habitats. Zohar et al. (2008) reported that cultured crabs had the same survival rate as the wild population; at the release sites, there was an increase in population size of between 50 percent and 250 percent. In addition, the cultured crabs grew quickly to sexual maturity, mated, and migrated from the initial release sites to spawning grounds, which led to them contributing to the breeding stock within five to six months post-release. Crabs released earlier in the summer grew faster and matured a year earlier than later releases, with survival rates ranging from 6 percent to 25 percent.

Overall, enhancement (increase over natural densities) ranged from 25 percent to 150 percent, while production rates ranged from 100 to 600 crabs per ha – more than twice the normal densities. Hatchery-raised crabs tended to have shorter spines and initially exhibited naïve behaviors but adapted quickly if given the opportunity. Another 215,000 crabs were released in 2007. The program's success is measured by the scientific progress made in understanding the production of crabs, and designing an optimal release strategy (Tweedley et al., 2017). Significant economic trade-offs were found with release size/stage. No information is available about scaling this up to a full program.

## Scallops, Japan and New Zealand

The scallop, *Mizuhopecten yessoensis*, also known as *Patinopecten yessoensis*, fishery in Japan collapsed in 1945 and has remained low in key regions. An enhancement program is currently run by fishing cooperatives in Hokkaido, Japan, to address the collapse. Scallop breeding grounds are seeded with a high density of juveniles and protected by rotating harvest arrangements and predator control, which has increased production from 40,000 tons to more than 300,000 tons per year. The success of this program is attributed to suitable habitat, survival rates of juvenile animals, low post-release dispersal, integration with other management tools such as rotating harvest and effective predator control. This is combined with releasing management authority as well as exclusive harvest rights to the fishing cooperatives (Ventilla, 1982; Uki, 2006).

The scallop, *Pecten novaezelandiae*, enhancement program in New Zealand allowed fishermen to change their management approach to quota-based individual harvest rights, which was combined with rotational seeding and harvesting. Cultured juveniles contributed greatly to the recovery; however, these were later replaced by natural recruitment as the population recovered (Drummond, 2004).

Since New Zealand allows for property rights, the Challenger Scallop Enhancement Company was formed in 1994 from scallop individual transferrable quota owners (Yandle, 2006). Their role in the fisheries was to manage all research and enhancement activities in consultation with the Ministry of Fisheries. They put in place a program to reseed beds in Tasman and Golden Bay, and a rotational harvesting approach was introduced with each bed only harvested once every three years. Millions of dollars were poured into the scheme, dredging continued to be a major gear/method for catching scallops, and a decade later the fishery seemed to be booming. Harvests bounced back as high as 800 metric tons in 1995.

After that, however, annual catches began to decrease (Figure 5). The last good year was 2002, when 700 metric tons were harvested. By then, commercial fishermen were no longer keeping to their rotational harvesting agreement, and the seeding program had failed. The Southern Scallop fishery (Area SCA 7) finally shut down in 2016, with only about 20 metric tons harvested. It has never reopened. Other areas have also seen declines in abundance and are in varying phases of closure. It is unclear why the fishery collapsed despite enhancement and co-management. There are several hypotheses, ranging from dredging and trawling damage to the scallop beds, toxic residue from chemical plants, and even a flood in 2011 that allowed for increased sedimentation over the areas where scallops thrived.

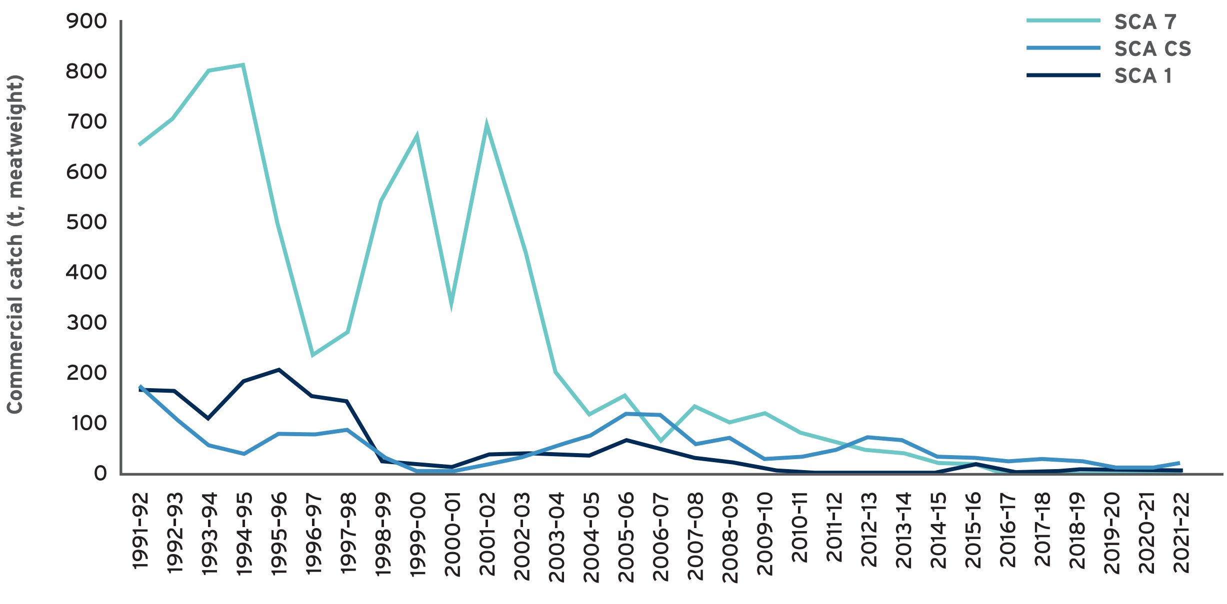


Figure 5: Historical commercial catch in the three main New Zealand scallop fisheries, Northland (SCA 1), Coromandel (SCA CS), and Southern (SCA 7) scallop fisheries from 1991 to 2022. The 2021–22 fishing year is incomplete. From Fisheries New Zealand (2021).

## Varied species, Korea

Fish stocks have been decreasing since 2000 despite various management measures; based on stock assessments, total production has decreased consistently from around 10 million tons in 1980 to 7.9 million tons in 2004. Despite the use of traditional management approaches, fish stocks failed to recover to their sustainable levels (Lee and Rahman, 2018). In response, the Korean Government established a fish stock rebuilding plan combined with conventional fish stock enhancement programs in 2005 (Lee and Midani, 2014; Lee and Rahman, 2018).

The Fish Stock Enhancement Program is one of the major tools for rebuilding fishery stocks carried out by the Korean Fisheries Resources Agency. The agency is involved in Fish Stock Enhancement Programs, including the construction and installation of artificial reefs, production and release of fish seeds, and building and management of marine ranches and marine forests (marine reforestation) to restore and recover fish stocks in Korea's coastal and offshore fisheries. In Korea, the main goal of Fish Stock Enhancement Programs is to increase fish stocks and fishermen's income by improving the marine environment and restoring productivity for the natural fish population. The artificial reef program was implemented in 1971 to increase fishery resources by creating habitats and spawning grounds. The fry stocking program has been operating since 1976 to complement and enhance the recruitment of fishery resources.

Between 1986 and 2012, 46 marine species were stocked. In areas where habitat was identified as limiting, artificial reefs were deployed. Approximately 3,000 fishing grounds were augmented; 55 percent used for fishing, with the remainder closed as nursery and breeding grounds. These are all managed jointly with the fishing communities. Using catch data only, the government firmly believes that this program has been successful for many species, including BSC, *Portunus pelagicus*; octopus, *Octopus vulgaris*; skate/ray, *Hongeo koreana*; and cod, *Gadus macrocephalus* (Lee and Rahman, 2018).

Among the 10 species analyzed, the catches of eight species increased by approximately 10 to 20 percent under the rebuilding plan compared to the initial stage, and the total recovery of catch for 10 species is estimated to be 442,486 metric tons. Once this amount is multiplied by the average market price, the annual increase in fishing revenue for each target species can be estimated. Considering the 10-year results, total fishing revenue was found to have increased to over $4,011 million for 10 species in 2016. No detailed information is available regarding the actual contribution of the hatchery-reared animals to the catch.

## Chinese white shrimp (prawns), *Penaeus chinensis*, more recently referred to as *Fenneropenaeus chinensis*, China

Hatchery releases of prawns have been made since 1984, both in their natural habitat and into new locations, with catch of released prawns contributing up to 90 percent of total landings depending on the region. The ratio of production costs to revenue reached 1:8.5 in the Yellow Sea and averaged 1:5.6 in the surrounding areas (Wang et al., 2006). The release of hatchery-reared prawns in China was successful because it increased the production of the commercial prawn fisheries. However, the size of the wild prawn populations in specific regions did not increase due to overfishing, and self-replenishing populations have not been successfully established in translocated areas. There has also been a shift from the central government financially supporting these efforts to a "user-pays" system in which program beneficiaries support the costs of releasing the animals. In this case, rebuilding wild prawn stock through improved management regulations supplemented by stock enhancement promises to be a more cost-effective answer to overfishing than the enhancement efforts (Wang et al., 2006).

The *Fenneropenaeus chinensis* fishery has become increasingly dependent on hatchery releases and the number of released *Fenneropenaeus chinensis* has increased every year (Wang et al., 2014). Changes in enhancement value were modeled using a published ecosystem model Object-oriented Simulator of Marine ecOSystEms (OSMOSE-JZB) to evaluate the impacts of *Fenneropenaeus chinensis* release in Jiaozhou Bay, China from a dynamic perspective. The results showed that artificially released individuals experienced high predation pressure during the first two weeks, and economic profit peaked when 198 million individuals were released. The modeled hatchery program yielded lower production with the increasing amount of *Fenneropenaeus chinensis* release. The temporally uniform hatchery release was more efficient than other hatchery release scenarios (e.g., increasing the released amount year by year) in a long-term hatchery program. *Fenneropenaeus chinensis* negatively impacted two large predatory fish, which recovered slower than small fishes after the release stopped. The study indicates that the effectiveness of *Fenneropenaeus chinensis* release cannot be enhanced by simply increasing the released amount.

## Red drum, *Sciaenops ocellatus*, USA

Red drum, *Sciaenops ocellatus*, enhancement in the USA is the world's largest marine fish enhancement program (Kitada, 2018). The red drum population reached an all-time low in the 1970s; to combat this decrease, a stock program was initiated in 1975 and has continued to this day. More than 600 million red drum fingerlings have been hatchery-produced and released in the coastal bays of Texas, averaging approximately 20 to 30 million per year. As a result of this enhancement effort, which was applied in combination with traditional management practices, the red drum population rebounded (Vega et al., 2011). A restocking program was also initiated in South Carolina in the late 1990s. The program followed a responsible approach and received national attention when it was recognized by the American Fisheries Society as an "Outstanding Sport Fish Restoration Project" (Smith et al., 2005). Approximately 800 million fish were stocked in September 2021; however, very little information is currently available about how the success of this program has been measured.

## Donkey ear abalone, *Haliotis asinina*, the Philippines

This exploratory enhancement project aimed to assess the suitability of different culture containers for nursery and grow-out culture of donkey ear abalone *Haliotis asinina*, in response to intense artisanal catches of this high-value product (Salayo et al., 2020). An enhancement program was initiated to use hatchery-produced seeds to rehabilitate the fishery through an exploratory enhancement program involving extensive stakeholder input. Much work was done before the start of the enhancement program, including on-site pilot studies, targeted release strategies, baseline data collection on the natural abundance of juvenile abalone in potential release sites, assessment of appropriate habitat and existence of natural food items, and understanding predator abundance. Between September 2011 and April 2015, 11,503 individual batch-tagged juveniles were released into Molocaboc Reef (protected zone) after acclimation. The results showed a remarkable increase in CPUE during the five-year monthly monitoring managed and run by local abalone divers (52.9 mean individuals in 2015, from 0 to 2 mean individuals in 2011). Spawning is assumed to have been augmented as mature animals remained in the area. The success of the program is attributed to the combined approach of improved management efforts, joint management initiatives, and area closures.

# Annex II: Lessons learned from clawed and spiny lobsters and non-portunid crabs

## Clawed and spiny lobsters

Research on the North Atlantic clawed lobster, *Homarus* sp., for cultivation and release programs has been conducted in Norway since the 1880s (Nicosia and Lavalli, 1999). The European lobster, *Homarus gammarus*, is a valuable fishery, but landings have exhibited clear signs of overexploitation during the last century (Green et al., 2013). The restocking of cultured juveniles has shown potential as a viable local management option; however, the major hurdle has been the technologically complex and expensive production of juvenile lobsters to a size suitable for release (Nicosia and Lavalli, 1999). Postlarval stage lobsters are too small to survive in the wild and must be raised until they are juveniles. It is possible to raise large quantities of lobsters to the postlarval phase, but juvenile production is too costly, mostly because of the need to hold them individually. Van der Meeren (2000) also documented behavioral differences between lab and wild-caught juveniles that would affect their capacity to survive in the wild, such as predator avoidance and shelter behavior.

Until recently, commercial attempts at farming have not been viable, mainly because of cost-prohibitive technical challenges which have been re-examined (Hinchcliff et al., 2021). There have been continual applied scientific research projects and technological advances in *Homarus gammarus* release and production aquaculture at both hatchery (broodstock husbandry and development, larvae, young juveniles) and ongrowing stages. These have encompassed husbandry, production techniques and equipment, hygiene and health management, feed development, juvenile behavioral training, and onward release strategy. Nevertheless, key knowledge gaps and challenges to scaling remain that require additional research, including how to improve the quality and quantity of juveniles in a more cost-effective manner.

Enhancement attempts for American lobster, *Homarus americanus*, have persevered for a much longer time, although repeated attempts at enhancement have not shown great promise. Castro (2003) released microcoded fourth and fifth stage lobsters over a five-year period combined with artificial reef habitats and found no effect. Behavioral deficiencies were also documented. However, public pressure to continue hatchery releases lasted until 2019. No stock enhancement has been done at a large scale for spiny lobsters.

The use of "casitas" as habitat enhancement for *Panulirus argus* during a sponge die-off in the early 1990s suggested that bottlenecks could be eased for postlarval lobsters (Eggleston et al., 1990; Herrnkind et al., 1999). Casitas have been used in Mexico and the Caribbean as fishing gear and aggregation devices in privately owned or cooperative-owned areas (Ley-Cooper et al., 2011; Gittens, 2017).

## Non-portunid crabs

Enhancement of crab populations is being conducted in many parts of the world. Crab cultivation is thriving in the tropics, using methods ranging from low-tech family operations in ponds, to high tech industrial hatcheries. One of the most notable is for Southeast Asia mud crab species *Scylla serrata*, *S. tranquebarica*, *S. paramamosain* and *S. olivacea* (Shelley and Lovatelli, 2011), which all support valuable fisheries.

## Mud crab, *Scylla olivacea*, the Philippines

Research by Lebata in 2006 evaluated the potential for enhancement in Naisud and Bugtong Bato, Ibajay, Aklan, the Philippines. The results of the stock enhancement trials showed that small-scale release can increase the abundance of mud crabs in a partly isolated mangrove habitat. Both wild and hatchery-reared crabs also exhibited limited post-release movement, supporting the overall conclusion that stock enhancement can be an effective tool in addressing declining fisheries resources. No recent information was found.

## Mangrove crab, *Ucides cordatus*, Brazil

Overfishing and mangrove degradation have contributed to the loss of the mangrove crab in Brazil. Lethargic crab disease further exacerbated the loss, causing mass mortality events (Ventura et al., 2008). Larval methodologies have been developed, but high mortality between zoea to megalopae and cannibalism have slowed down efforts at enhancement.

## Chinese mitten crab, *Eriocheir sinensis*

The Chinese mitten crab is a catadromous crustacean with a lifespan of approximately two years and a high nutritional and economic value in China (Cheng et al., 2008). In the natural environment, it grows in fresh water until maturity and then migrates into saline water to spawn. The mitten crab is exclusively cultured in China for stock enhancement purposes. Initially, wild megalopae were collected and raised in hatcheries prior to release into freshwater systems and captured one year later (Cheng et al., 2008). From the early 1970s to the mid-1980s, wild-caught megalopae in the Yangtze River were released into open lakes, and farmers ultimately benefited from this stocking strategy (Cheng et al., 2008). With new technology and methods, broodstock are now maintained in captivity and larvae are produced in the hatchery. The total production of this species increased from 8,000 metric tons in 1991 to 714,400 metric tons in 2012; the industry is worth an estimated $5 billion annually.

## Alaskan king crab, *Paralithodes* spp.

Alaskan king crabs are some of the most valuable crustaceans in the world. Stocks of these species crashed in the 1980s and have failed to recover since (Stevens et al., 2001; Daly et al., 2009). Aquaculture techniques were developed for *Paralithodes camtschaticus* and *P. platypus*. Production is limited as these species are cannibalistic and require special rearing conditions. Survival in the wild is habitat-specific and believed to be limiting (Stevens, 2006). Large-scale stock enhancement programs were not believed to be economically feasible, and no full-scale releases have occurred, although research has continued.

In 2022, there were major changes in the fisheries law, allowing nonprofits to pursue mariculture enhancement or restoration projects for shellfish species such as abalone, razor clams, sea cucumbers, and king crab. It would be the first time in Alaska's history that people could raise animals such as crabs in hatcheries and release them into the wild to support commercial fisheries. Chris Long, a scientist at the NOAA Alaska Fisheries Science Center laboratory in Kodiak, has been experimenting for several years with projects that might show how to enhance natural crab stocks with hatchery-raised larvae (Long et al., 2018). Much of his work focuses on red king crab in Kodiak, a region where the once-thriving king crab fishery crashed in the 1980s and never recovered. In experiments so far, very few of the larvae have survived after being spread in the water, at best about 2 percent.

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## Assessing shortfalls and opportunities

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