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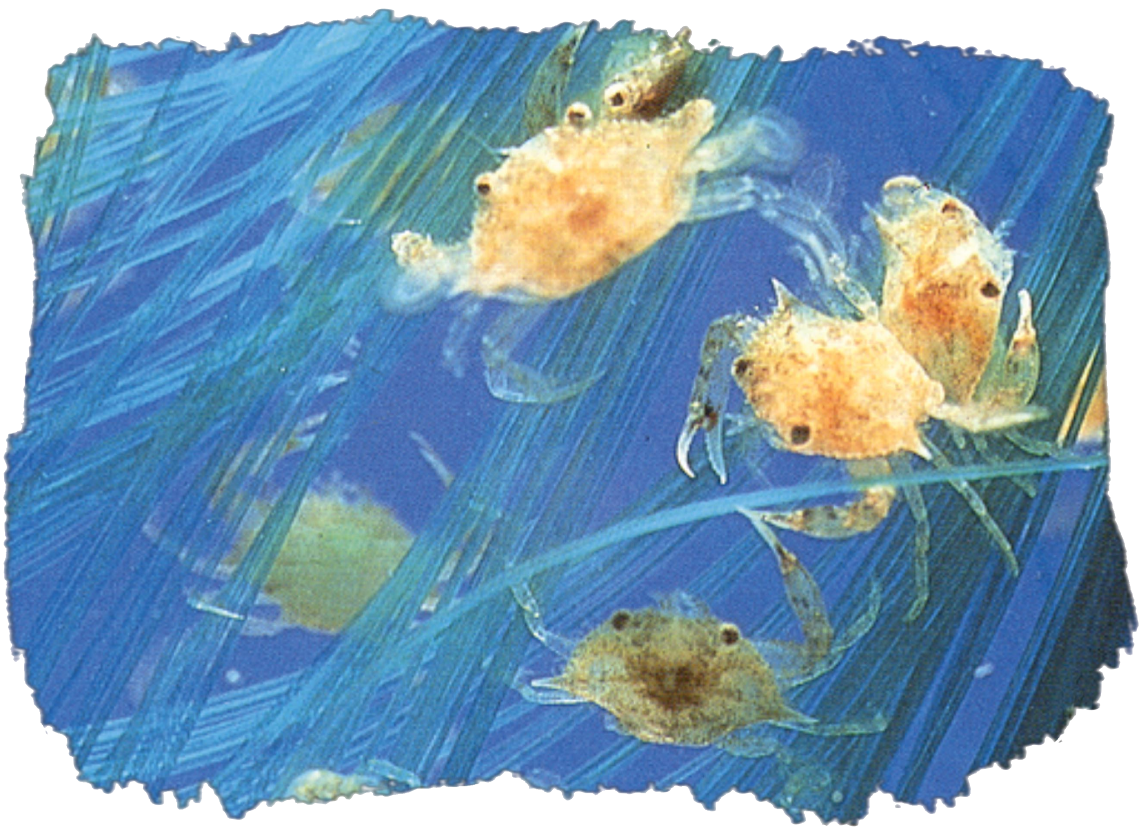
Japanese Hatchery-based Stock Enhancement: Lessons for the Chesapeake Bay Blue Crab



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Japanese Hatchery-based Stock Enhancement: Lessons for the Chesapeake Bay Blue Crab

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Preface

Maryland's research community has been involved with a wide range of issues relevant to the Chesapeake Bay's blue crab fishery. Over the past two years, these activities have occurred within the context of a heated public debate over implementation of new fisheries regulations in response to a declining blue crab stock. The focus of these research programs has ranged from understanding how the fishery functions to important aspects of the biology and ecology of *Callinectes sapidus*. A recent proposal to develop a large-scale release program of hatchery-produced blue crabs in the Chesapeake Bay has sparked considerable, and at times contentious, discussions in the research and management community — particularly with regard to the issue of feasibility. One of the important benchmarks discussed has been the long-standing effort by Japanese scientists to cultivate crab species and enhance natural populations. Given the importance of the Japanese experience, Maryland Sea Grant provided funding for three scientists to visit Japan in August 2001. The members of the team were drawn from different academic disciplines and institutions, and view the issue from different perspectives. They spent ten days touring facilities in Japan, and their observations are captured in this report. The team reached consensus on many issues and diverged in opinion on others. Undoubtedly this thorough and thought-provoking report will provide a reference point for continuing discussions both within and outside the research community. Maryland Sea Grant is grateful for their efforts and for their contributions to this important issue.

Jonathan G. Kramer, Ph.D.
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Report Highlights

Findings

- For the past 30 years, the Japanese Sea Ranching Program has fostered the development of technologies to cultivate large numbers of the swimming crab, *Portunis trituberculatus*. State of the art facilities throughout Japan now produce approximately 60 million C-1 instars (~5.0 mm carapace width) annually. Prior to 1990, these C-1 crabs were released in great numbers for stock enhancement purposes. Japanese scientists now believe that these efforts were largely ineffective. Since 1991 hatcheries have modified their approach to include secondary rearing from the C-1 to C-4 stage (~17 mm carapace width) prior to release. Over the last decade stocking efforts focused specifically on C-4 juveniles have resulted in releases of 28-42 million crabs annually.

- Assessments of three stock enhancement case studies representing a range of size, physical characteristics and fisheries — Hamana Lake, Osaka Bay, and Okayama Prefecture — suggest that releases of C-4 juveniles in small scale systems (Hamana Lake, Osaka Bay) may be sustaining low catch levels and subsidizing what are presently very reduced levels of reproductive stocks. Evidence for enhancement to historical levels has not been found, although habitat degradation may be contributing to an overall reduction in carrying capacity in these systems. In the large system (Okayama Prefecture), the pattern of landings over the past 30 years suggests decadal oscillations (most likely climatic) in crab stocks; hatchery releases appear to have had little impact on crab stocks and subsequent fishery yield.

- The long-term investment by the Japanese — at the federal, state and local levels — has built significant capability and has led to a far greater understanding of growth and reproduction in *P. trituberculatus*. Until very recently, however, there has not been a concerted effort to assess the impacts of stock enhancement programs on fisheries. Coupling production and enhancement efforts with assessment is an essential prerequisite to understanding fully the impact of investments in restoration efforts of this type.

Implications for Chesapeake Bay

- With regard to the feasibility of enhancing crab populations in Chesapeake Bay, the team diverged because of differing views on the applicability of the Japanese data and differing assumptions about the nature of crab population(s) in Chesapeake Bay. Central to this divergence were differing views of the implications of scale, the importance of localized populations of blue crab and the significance of spatial and temporal dispersal patterns.

- One view holds that focused efforts designed to enhance local, reproductive populations is feasible. In particular, augmenting juvenile crabs in subestuaries with hatchery-reared individuals would supplement local sub-populations in a way that overcomes dispersal and the high-mortality rates associated with larval development and should therefore positively impact fishery yield by enhancing the recruitment to the broodstock.

- The other view holds that because the scale of Chesapeake Bay crab stock is immense compared with the Japanese ecosystems and because the Chesapeake Bay blue crab population replaces itself as a single unit, hatchery-based efforts cannot enhance populations in the face of natural productivity. The most effective tools for sustaining the crab population are scientifically-based fisheries management and programs of habitat restoration.

- Despite this divergence, there was consensus among the authors that there are compelling reasons to develop local rearing facilities to produce releasable juvenile blue crabs (~100,000-1,000,000/year) for research purposes. Such facilities would greatly improve our understanding of the biology of this organism and provide opportunities to develop better tools to manage the fishery in Chesapeake Bay. In addition, the team agreed that habitat restoration and strong fishery management are essential if sustainability is to be achieved in the Chesapeake blue crab fishery.

Executive Summary

Introduction

The decline of the Chesapeake Bay blue crab fishery over the past decade has catalyzed numerous debates throughout the region. *Callinectes sapidus* represents the most important Bay fishery, and in recent years the blue crab stock has hovered near the historical low-point recorded in 1968. Faced with this condition, in 1999 the governors and legislatures of Maryland and Virginia initiated a broad-based effort to establish new criteria for the Baywide management of this resource. Over the past two years, the Bi-State Blue Crab Advisory Committee (BBCAC) forged a unique partnership that linked scientists, managers and watermen in an effort that has led to the implementation of new harvest regulations designed to set thresholds to protect spawning stocks in the Bay. These precautionary thresholds and related regulations are strongly endorsed by the three authors.

As the bi-state process developed, it became clear that there remained a number of key unknowns about this very complex organism and its fishery. Maryland Sea Grant, the NOAA Chesapeake Bay Office, the Maryland Department of Natural Resources, and research entities have mobilized resources and rapid progress is being made towards improved science and management of blue crabs. In parallel to these research efforts, questions emerged regarding the potential to use hatcheries as a means of enhancing blue crab populations in Chesapeake Bay. Funding from the Maryland legislature and private industry was provided in 2000 to initiate a research program focused on rearing blue crabs in closed systems and on developing a better understanding of reproductive biology, growth and mass cultivation, as well as to provide a foundation for potential large-scale hatchery production of juvenile crabs. Discussions regarding the role and feasibility of hatcheries as a viable element in the management of Chesapeake Bay blue crabs very rapidly reached the stage of a heated and at times publicized debate within the academic community.

One of the rationales for undertaking an effort to develop hatchery technology for *C. sapidus* was that hatchery rearing and enhancement had been successful for a similar species — the swimming crab, *Portunus trituberculatus* — in the Seto Inland Sea of Japan. While some information was available in the scientific literature, there was very little data upon which to judge the success or failure of the Japanese effort and perhaps more importantly to assess its implications for blue crab management in Chesapeake Bay. With this in mind, Maryland Sea Grant provided funding for three researchers to travel to Japan in the summer of 2001 to assess the crab hatchery program. While all three members of the team were engaged in some aspect of blue crab research, all had very different scientific backgrounds. Their contrasting expertise provided an opportunity to view the Japanese experience through very different lenses. The team was charged with the following tasks:

1. To visit a representative cross section of crab hatchery operations in the Seto Inland Sea and other areas in Japan and to determine the context, extent and success of crab rearing facilities.

2. To determine how crab stock enhancement was implemented over its 30-year history in Japan and if it had an impact upon the swimming crab fishery.

3. To determine if and how this information is relevant to the feasibility of hatchery-based enhancement for Chesapeake Bay blue crabs.

The research team returned with a tremendous amount of information. There was clear agreement on many issues and a shared interpretation of most of the Japanese data. That said, divergent interpretations and opinions were also apparent. As much as is possible, this report summarizes the team's findings, points of agreement and differing views.

Findings and Conclusions

Context, Extent and Success of Crab Rearing in Japan

According to the research team, fisheries enhancement efforts in Japan take place within the context of a highly modified coastal environment with severe degradation of important habitat for fisheries reproduction and recruitment. Consequently, controlled rearing of commercially important species has a long history and plays an important role in the coastal economy. Government investment in the infrastructure required to support this effort is extensive and occurs at both the national and prefectural (state) level. Japan's sea ranching effort is a capital-intensive operation that itself is integrated into a system designed to cultivate and release a wide range of marine species. The world leader in the development of artificial propagation methods for marine fishes and crustaceans, Japan's mass-production methods for *Portunus trituberculatus* extend back 30 years. A close linkage exists between the propagation and releases of *P. trituberculatus* and the fishing cooperatives that ultimately harvest them. The cooperatives have direct input into decisions regarding production levels and may provide support or actually operate small local crab hatcheries. In view of the service role that enhancement programs provide fishing cooperatives, the aim of the Japanese release programs is towards fishery enhancement ("put and grow") rather than enhancement of stock productivity.

The Japanese have implemented rearing facilities capable of producing approximately 60 million C_1 instars (~5.0 mm carapace width) per year. Production facilities range from a large-scale, nationally supported facility (Tamano Station) capable of producing as many as 10 million C_1 instars/year to smaller scale, prefecture-based operations that produce on average about 3 million C_1 instars/year. It was clear that the investment in hatchery technology and long-term support for research has facilitated the development of an extensive knowledge base — much of which has been translated directly into practical applications for rearing and grow out. The science of crab cultivation and the associated knowledge of the reproductive biology of *P. trituberculatus* is very advanced in Japan.

Implementation and Impacts

The Japanese swimming crab stock enhancement program has evolved over its 30-year history. The early success of rearing technologies led to a concerted effort to release millions of C_1 instars into coastal ecosystems. While this strategy lasted for nearly 20 years, there was very little systematic collection of key data on the fate of released crabs. The discovery that survivorship of the C_1 instars was extremely low (<1%) led to a major modification of protocols and associated technologies. By the early 1990s, secondary rearing to the C_4 (~17 mm) stage prior to release was implemented by hatchery operators throughout Japan. Secondary rearing facilities achieved 12-61% survival of C_4 instars from C_1 instars. During the period 1991-1997, 28-42 million C_4 were released annually throughout Japan. This shift in strategies has been accompanied by a recognition of the need for a more concerted effort to evaluate the impacts of the enhancement program on fisheries.

While data were not complete nor definitive for any of the local programs visited by the research team, three different case studies provide insights into the efficacy of hatchery enhancement in Japan.

▶ ***Hamana Lake.*** Hamana Lake, a small coastal lagoon with a single inlet to the sea, experienced a dramatic (10-fold) decline in swimming crab harvests in the mid 1980s; the decline was thought to be due in part to changes in the physical dynamics of the system that limited entry of larvae and juveniles from outside the lagoon. In addition, resort and residential development pressure, coastal modifications, and low flushing rates within the system may have resulted in an increased duration of hypoxic events. Efforts to stock the system with C_4 instars began shortly after the population crash and at present about 1.4 million juvenile crabs are released into the system each year. A mark-recapture study in 1998 and a more long-term cohort analysis conducted between 1992-1998 have provided information regarding the contribution of stocked crabs to local fisheries. The recapture rates in the fishery of released C_4 instars was estimated to range from 0.3-2.2% and suggests that the stocking efforts are responsible for an 18% contribution to the fishery as it stands now in Hamana Lake. Based upon analysis of long-term trends in the harvest data, the stocking effort does not appear to be enhancing the fishery as annual harvests remain near or below the levels found when the fishery experienced its large decline. Evidence may suggest that the effort has helped to sustain the level of the fishery following its collapse in this ecosystem.

▶ ***Osaka Bay.*** Osaka Bay is a heavily impacted, mid-sized ecosystem with profoundly modified shorelines and severe degradation of natural habitat. The crab fishery has seen large historical declines — most recently in the late 1970s — that are likely associated with habitat loss, and periods of degraded water quality. Enhancement efforts using C_3-C_4 instars were implemented, and since the early 1990s approximately 0.7 million/year juvenile crabs have been released. Data for long-term trends in crab harvests in Osaka Bay suggest that the releases have not led to an enhancement in fisheries to historical levels prior to collapse in the fishery. Recently, extensive studies have provided details into the dispersal, growth and survivorship of released crabs. Juvenile crabs released into shallows showed limited dispersal over their first month at large, grew rapidly, and attained harvestable size within their first year of life. Employing these data, a fisheries model for Osaka Bay predicted a recapture rate of 31.3% for released crabs in 1990, with a concurrent contribution to 1990 landings of about 59%. This rate is sensitive to fishery model assumptions, but suggests that hatchery releases could be subsidizing to a substantial degree the severely depressed Osaka Bay fishery.

▶ ***Okayama Prefecture.*** Okayama Prefecture's segment of the Seto Inland Sea is the largest and most open of the systems examined and also supports the largest crab fishery (~2-10 fold greater). Early efforts focused upon the release of C_1 instars and there was an apparent increase in landings. However, Japanese scientists reported that this correlation was unexplained and attention since 1991 has been on the release of larger C_4 instars reared in coastal impoundments. Approximately 1 million juveniles are currently released per year. The Okayama fishery has experienced wide variations over the past 30 years and at present harvests are in a period of decline. Studies based upon cohort analysis suggest that the recapture rate for released crabs was 5.7%, with a concurrent contribution to the fishery of 9%. Recent studies suggest that most released crabs are retained within a fairly small area (5-20 km of release) over a period of two years, suggesting to some on the team that the geographical range or ambit of stocks of this species is restricted.

The three facilities studied provide a number of key insights and there was general agreement among the group on several points. These include:

- Output from hatcheries in the Seto Inland Sea has been substantial, as have releases of both C_1 and C_4 instars. However, the effort has not been integrated with a clearly defined program to assess effectiveness. Recent studies have begun to address this issue and should be closely monitored. Such integrated efforts are essential for any program using hatcheries as a way to enhance natural stocks.

- The development of mass rearing capabilities has been a key factor in the development of a very strong knowledge base on the reproduction and biology of *P. trituberculatus*, and is a useful element in studies to assess key parameters in the natural environment. With sufficient resources, this technology could be readily applied to the development of similar cultivation systems for *Callinectes sapidus*.

- Recent studies suggest that release of hatchery raised C_4 instars has been a factor in the maintenance of the crab fisheries at their present (albeit very depleted) levels in two cases (Hamana Lake and Osaka Bay).

- Although this effort has been extensive, enhancement of collapsed fisheries to historical yield levels has not been realized through hatchery releases into these highly modified systems. However, due to degradation of habitats it is not clear what the carrying capacities of these subsystems are, though they have fallen below historical levels.

Implications for Chesapeake Bay

Interpretations of how Japanese experiences and data relate to the Chesapeake Bay differed among the scientists participating in this fact-finding mission. A point of agreement was that enhancement strategies should not be directed only at increasing fishery yields, but should be directed at enhancing reproductive potential of the Chesapeake Bay stock. As noted earlier, the lenses through which each viewed the issue led to a focus on specific aspects of the enhancement effort there. Two relatively distinct opinions and interpretations emerged. Central to these divergent views was the importance of localized populations in Chesapeake Bay relative to a unified Baywide stock of blue crabs. This divergence led to very different conclusions:

One view holds that examination of the fisheries data for the three case studies suggests that *P. trituberculatus* has a limited dispersal and rapid growth rate, and accordingly is more amenable to efforts designed to sustain small-scale local fisheries through large localized releases, followed by intense exploitation. The case for Chesapeake Bay presents a different set of constraints based in great part upon the fact that *C. sapidus* has a very large seasonal and annual dispersal range and can be managed only as a single Baywide stock. Because the Chesapeake Bay's population of blue crabs is so much larger than the Japanese stocks, efforts to enhance the population — given the estimates of hatchery contributions to the fishery in Japan — would require such large numbers of juveniles that it would make the effort unfeasible on this scale.

The other view holds that definitive data on the Japanese effort is only now emerging and, as such, provides a guide for ways to proceed in Chesapeake Bay. The importance of localized crab subpopulations has been underappreciated in the Bay, as has the use of protected areas to provide sanctuary for reproductive populations. Based upon the success of rearing technology in Japan, it is feasible to use hatchery-raised juveniles to enhance specific local populations or reproductive females in specific areas and, in conjunction with strong fisheries management, thereby achieve positive impacts on the fishery.

Introduction

Recent declines in Chesapeake blue crab landings, and evidence for declines in spawning stock and recruitment (CBSAC 2001; Sharov et al. 2001) have prompted actions for increased regulation of harvest, increased habitat management and restoration, and improved scientific understanding of factors that control blue crab production. In addition, seafood industry representatives, state and federal legislators, and some scientists have suggested that the blue crab stock in Chesapeake Bay might be enhanced artificially through controlled spawning, hatching and rearing technologies, and release of juvenile crabs into natural ecosystems. This use of hatchery-based stock enhancement for a variety of species is controversial (Hilborn 1999; Leber 1999; Hilborn and Eggers 2000; Secor et al. 2000a). Critics note that research has focused mainly on hatchery production methods without adequate assessment or analysis of factors affecting successful survival of released juveniles. Advocates of stock enhancement for Chesapeake Bay blue crabs point to the large hatchery-based ranching program undertaken in Japan as a model. Some 28-42 million juvenile swimming crabs — *Portunus trituberculatus* — are released in Japan each year (since 1992, Ariyama 2000). Juveniles (c. 15-20 mm carapace width, CW) are released at numerous coastal locations within the Seto Inland Sea and other areas including the islands of Kyushu, Shikoku, and along the south-eastern coast of Honshu (Figure 1). Throughout most of the nearly 30-year history (1973-present) of Japan's Sea Ranching Program, there has been successful development of hatchery production methods but little critical evaluation of the effects of hatchery releases on stock enhancement (but see Ariyama 2000, Okamoto unpubl ms).

To further evaluate the Japanese approaches of using hatchery technologies for supplementing portunid crab stocks and the potential lessons for hatchery technologies in Chesapeake Bay, we traveled to Japan during July 2001; we visited hatcheries involved in large-scale production of juvenile portunid crabs and interviewed Japanese scientists who have conducted research on aspects of hatchery-based enhancement. Because Portunid crab markets in the U.S. are increasingly international, we begin by comparing portunid crab fisheries among the United States, Japan, and other major national producers. The Japanese Sea Ranching Program is then presented in the context of fisheries enhancement and management in Japan; particularly important is the government's role in providing considerable support for the research and physical infrastructure necessary to rear millions of juvenile swimming crabs. We then discuss three cases of hatchery-based stock enhancement in Japan for systems that vary in fishery yields, size, geomorphology and methods used to evaluate hatchery contribution to the catch. Finally, we apply lessons learned from Japan's experience to evaluating the issue of artificial propagation of blue crabs and the enhancement of their populations in Chesapeake Bay.

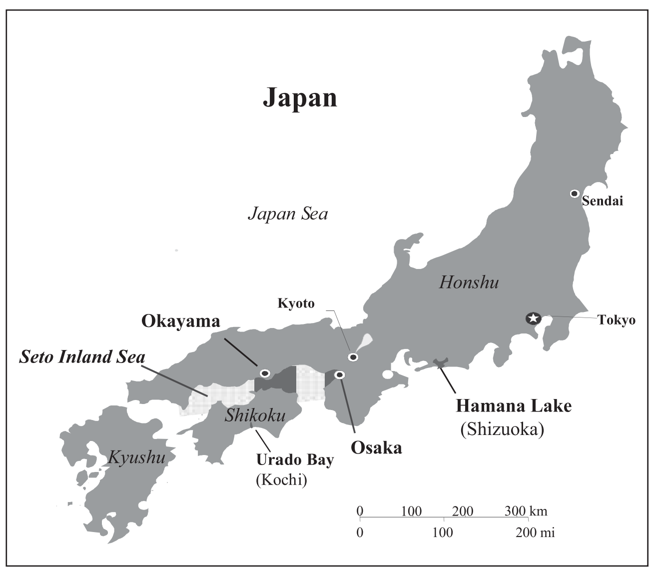

Figure 1. Case study sites where Japanese swimming crab P. trituberculatus *hatchery-based enhancement was evaluated: Okayama Prefecture portion of Seto Inland Sea, Osaka Bay, and Hamana Lake. Urado Bay, site of a mangrove crab enhancement study is also shown.*

World Fisheries for Swimming Crabs

Worldwide fisheries for swimming crabs (Crustacea, Decapoda, Brachyura, Portunidae) are dominated by three species: *Portunus trituberculatus* (Japanese "gazami")(ca. 50%), *P. pelagicus* ("blue swimming crab")(ca. 25%), and *Callinectes sapidus* ("blue crab")(ca. 25%). In Japan and elsewhere, other portunid species are harvested and locally marketed, including several species exhibiting large adult size (e.g., *Scylla serrata* and *S. tranquebarica* in Japan and the Indo-west Pacific, several intermediate adult size *Callinectes* species in the Caribbean and Americas) and more diminutive species (e.g., *Carcinus maenas* in Spain, *Charybdis* spp. in Japan). The fisheries of the three dominant species appear to have grown over the past three decades, but harvests of the two *Portunus* species have increased at a more rapid pace than for *C. sapidus* (Figure 2). The reported world landings of *P. trituberculatus* are dominated by China (>90%), while Japan's catch represented less than 2% of the harvest during this period (Figure 3). Changes in reporting appear to account for some of the increase in landings for *P. trituberculatus*; the increase in 1987 is due to China, which had not reported landings prior to that year. In the mid 1990s the Chinese catch again suddenly doubled, and it is not clear whether this large increase resulted from a change in reporting methods as opposed to a real increase in landings. Watson and colleagues (Watson and Pauley 2001, Watson et al., 2001) concluded that reporting of nominal landings in China may be substantially inflated due to the motivation structure for local fisheries officials. Indeed, total coastal zone fisheries in China increased dramatically by four-fold during the period 1987-1999. During this same period, Chinese harvests of *P. trituberculatus* increased 2.5-fold from 108,000 to 270,000 metric tons (t) (FAO 2000). Dominant contributors to the world catch of *P. pelagicus* were China, Indonesia, the Philippines, and Thailand. The market for this species has expanded considerably with the importation of processed crab meat into the U.S. (Petrocci and Lipton 1993). Chesapeake Bay (Maryland and Virginia) continues to be the single largest producer of *C. sapidus*, but its contribution to world harvests has declined in recent years from 45% in 1990 to 27% in 1999. For the period 1990-1999, Chesapeake Bay landings of *C. sapidus* were 10-fold greater than the total Japanese production of *P. trituberculatus*, and 19-fold greater in comparison to the Seto Inland Sea, a comparably sized system in Japan but with substantially different geomorphology and ecology (Figure 1).

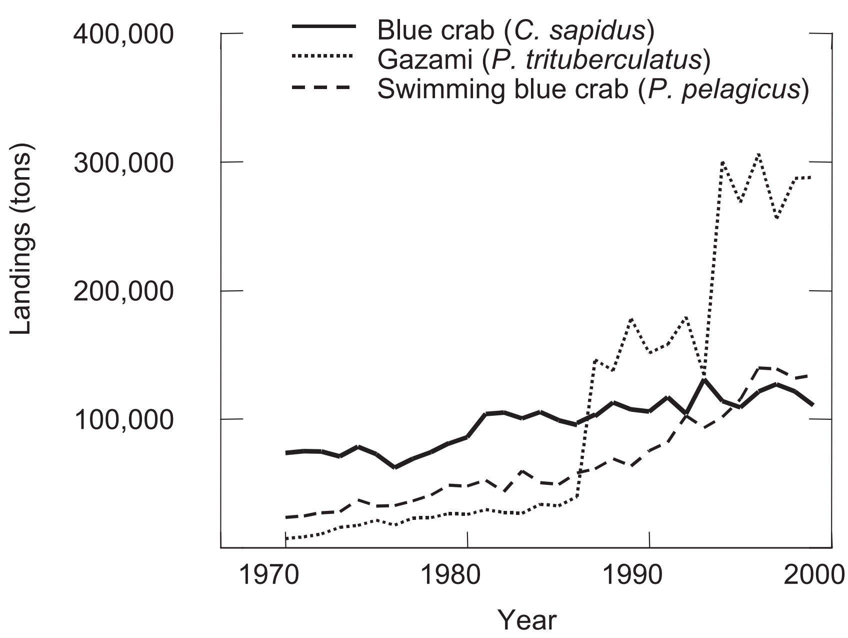

Figure 2. World harvests of dominant swimming crab stocks (FAO 2000).

Japanese Sea Ranching Program

In an effort to enhance its fisheries, Japan releases more hatchery-produced swimming crabs than any other nation: 28-42 million juveniles per year. The Seto Inland Sea Ranching Program was instituted in 1963 as a national initiative to enhance fisheries through mass production and release of young-of-the-year juveniles into coastal waters (Nose1985). The goals underlying this program were to:

1. Control fertility and timing of reproduction.
2. Enhance embryo and larval survival and growth by rearing them in artificial systems (primary rearing).
3. Acclimate and protect post-larval juveniles in semi-natural intermediate culture systems (secondary rearing).
4. Release juveniles into coastal systems at a size, place and time that allows them to most efficiently grow, survive and contribute to coastal fisheries.
5. Develop resource management strategies to maximize the return of released juveniles in fisheries.
6. Evaluate the effectiveness of hatchery-based enhancement.

To implement these goals, an array of research and hatchery stations now exists in Japan, consisting of 16 National Fishery Research Stations, 53 prefectural (analogous to states in the USA) Fishery Research Centers, and numerous hatcheries operated by local fishing cooperatives. Generally, the National Stations focus almost exclusively on the goals associated with propagation (goals 1-3), and these stations have developed techniques to produce juveniles of more than 80 marine species, including such difficult species to propagate as squid, eel, and bluefin tuna. The goals of mass production of young-of-the-year juveniles, as well as evaluating and maximizing fishery returns of released crabs and other species, typically have been left to the prefectural centers. Early focal species of national and prefectural stations were red sea bream (*Pagrus major*), Japanese flounder (*Paralichtys olivaceus*), tiger puffer (*Takifugu rubripes*), Japanese prawn (*Panaeus japonicus*), and portunid crab (*P. trituberculatus*). These species continue to dominate hatchery releases by prefectures and fishing cooperatives throughout Japan (Fushimi 1998).

Beyond research and development of new and improved methods for artificial propagation, National Stations serve

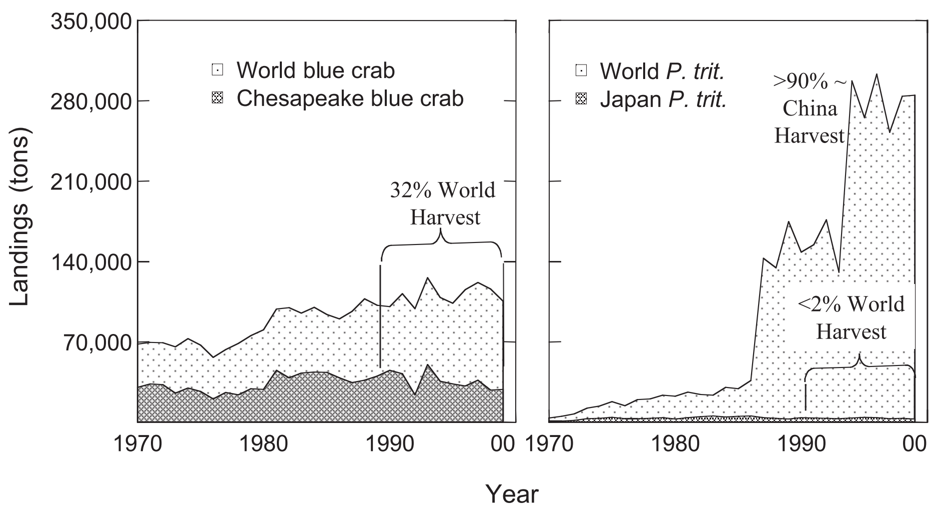

Figure 3. World harvests of blue crabs C. sapidus *and gazami* P. trituberculatus *(FAO 2000).*

as important production centers themselves. The Tamano Station on the Seto Inland Sea is the single largest production center for juvenile *Portunus trituberculatus*, producing 10 million 1st crab instars (C_1, 4.5-5.0 mm CW) each year, which are then grown up in secondary rearing to 4th-5th crab instar (C_{4-5}, ca. 17 mm CW) and supplied to Prefectures for release throughout western Honshu. Timing of reproduction of *P. trituberculatus* is controlled in the hatchery so that juveniles are released during early summer in advance of most naturally produced juveniles (Figure 4). This process in turn allows released juveniles a longer growing season and accelerates their entry into the fishery in their first fall. The Tamano Station continues to refine and communicate practical methods for rearing *P. trituberculatus*, and recently produced a comprehensive manual on propagation and hatchery methods (Hamasaki 2000).

Prefectural Farming Fisheries Centers are the principal producers of *P. trituberculatus* juveniles. Eighteen prefectural centers in Honshu, Shikoku and Kyushu (Figures 1, 5) produce ~60 million C_1 juvenile crabs each year (Fushimi 1998). As with the National Stations, it is important to note that the prefectural centers are multi-species facilities, typically producing other species such as Japanese prawn, Japanese flounder and sea bream in concert with *P. trituberculatus*. Prefectural centers vary in size, and staff (typically 8-12), but common features we observed included a seashore location; large pumping, filtration, and aeration systems; automated tank cleaning systems; raceways for crab brood stock; large rearing systems for C_1 crabs (typically between 100 and 200 m^3); and similar sized tanks for rearing live feed (e.g., phytoplankton and rotifers) in support of crab rearing. Most tanks are constructed of poured concrete and housed in large warehouses. Due to the seashore location of these facilities, capital costs are high. Economic data available for the Kagoshima

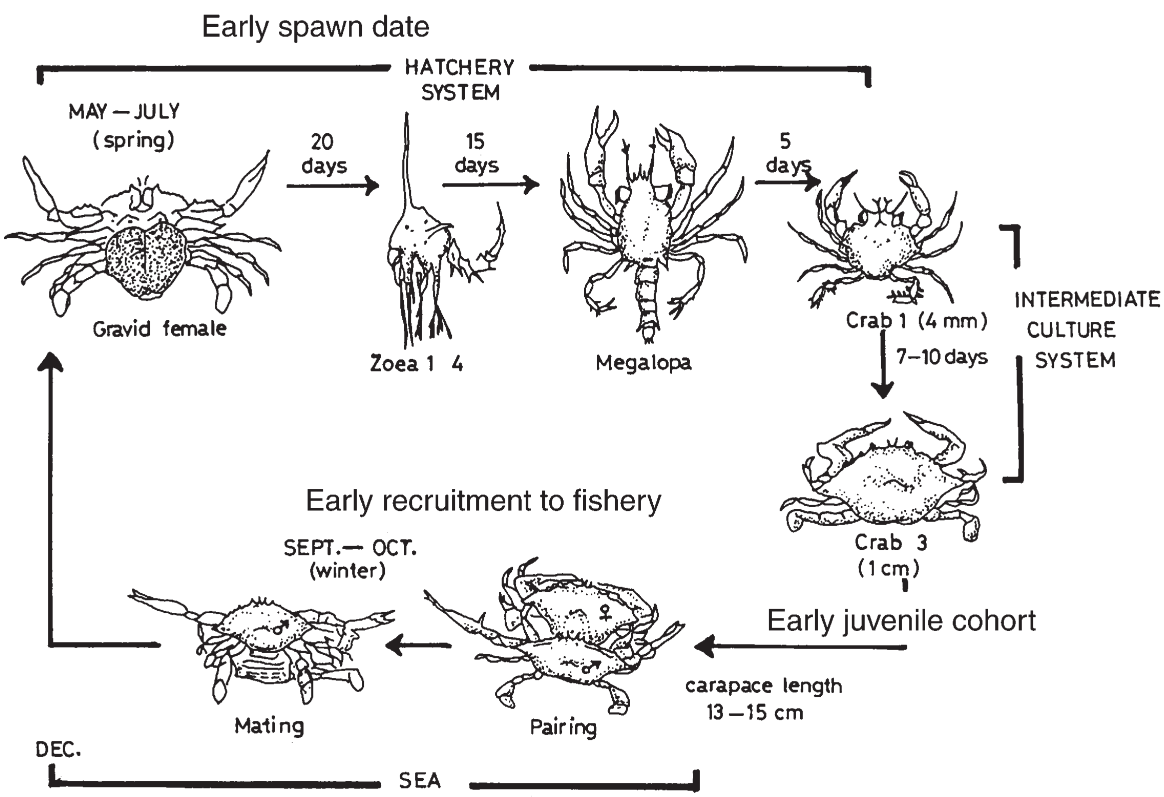

Figure 4. Sea Ranching Concept for Japanese gazami P. trituberculatus. *Intermediate culture refers to "secondary rearing" in text. Typically, C_4-C_5 crabs are released following secondary rearing. Note that hatchery-released crabs are expected to enter the fishery and contribute to the reproductive stock during their first fall of life. Diagram from Aileen et al. (2000).*

Measurement of Hatchery Contribution

Hatchery based enhancement is typically centered on two goals: (1) Enhancement of a fishery (also called put-grow-and-take strategy) and (2) Enhancement of the population (typically termed stock enhancement). Although the stated overall goal of Japan's Sea Ranching Program is stock enhancement, release and evaluation strategies focus on the issue of whether released juveniles are contributing to catch. Fishery contribution is estimated as the number of hatchery fish harvested as a proportion of the entire (hatchery + wild) harvest. Contribution of released juveniles to a fishery entails two events: (1) Released juveniles grow and survive to a harvestable size ("post-release survival"); (2) After attaining a harvestable size, released crabs are in fact harvested ("harvest recapture rate"). Two general approaches for estimating fishery contribution in this report are: (1) Direct approach, where released juveniles have a unique attribute (e.g., tag or size) that can be identified in harvested crabs; (2) Modeling approach, in which growth and survival into the fishery are directly estimated and coupled with a harvest model that specifies the probability that a harvestable crab is landed.

A common example of the direct approach for estimating fishery contribution is the cohort method, in which a pulse of similar-sized released juveniles makes up a unique size fraction in the size distribution of landed crabs. This cohort of similar sized hatchery crabs can sometimes be distinguished from wild cohorts in the fishery. By tallying hatchery cohort(s) as a proportion of total catch, fishery contribution can be estimated. Problems with the cohort methods arise when size distributions between hatchery and wild cohorts overlap broadly, and when growth rates among individuals are variable. A more rigorous method is to tag released crabs, as done in Hamana Lake, and then sample landed crabs for these tags. Precision in the estimate of fishery contribution rate here will be dependent upon the sampling rate of the fishery (number of crabs examined for a tag versus total number of crabs harvested) and the recapture rate (number of tagged crabs recaptured versus number of crabs tagged).

The modeling approach first determines the probability that a released juvenile crab will survive and grow to a harvestable size and multiplies this estimate by the number of released juveniles to calculate the number of hatchery crabs entering the fishery. Secondly, the modeling approach estimates the likelihood that a hatchery crab, once attaining a harvestable size, will in fact be harvested. This approach is as accurate as the component estimates of survival, growth, and harvest probabilities. Because methods of release, early survival and growth conditions, and fishery circumstances are expected to vary substantially year to year, this method should be verified by using direct methods for estimating fishery contribution. (See discussion of modeling approach for Osaka Bay, p. 27.)

Fishery contribution is not one in the same as fisheries enhancement. It only specifies that hatchery individuals are entering the fishery and being captured. There is evidence from salmon and flatfish release studies that hatchery fish can in fact displace wild fish in terms of survival and growth. In addition, habitat productivity waxes and wanes, which can lead to large variations in survival and growth of both hatchery and wild cohorts. Thus, fisheries enhancement requires broader-scale information on interactions between hatchery and wild individuals as well as changes in ecosystem carrying capacity. For similar reasons, analysis of fishery enhancement by correlating release numbers with catch levels is problematic. A positive or negative correlation may have more to do with changes in habitat productivity or the status of the wild population than the absolute numbers of hatchery individuals that enter the fishery. — *David Secor*

Prefectural Center (a typical center focused on production of red sea bream) put its assessed value in 1990 at $9.5 million, and annual operating costs were $470,000 (Ungson et al. 1993).

Prefectures are also responsible for secondary rearing of juveniles from C_1 (~5 mm CW) to C_4 (~17 mm CW) crab instar stages. Prior to 1991, C_1 instars were released directly; however, subsequent research showed that early instars were highly vulnerable to predation losses because they had not yet settled to benthic habitats (Karakawa 1997). In shallow, tidal, sandy beach experimental areas, which represent natural nursery habitat for *P. trituberculatus*, Ariyama (2000) conducted a series of intensive release-recapture trials. He reported that releases of 464,000 C_1 juveniles in 1981 resulted in no settled crabs one week after release. In 1982, only 2% survival was estimated one month after 97,600 C_3-C_4 crabs were released. In contrast, for 84,000 C_3 and 246,000 C_4 juveniles released after careful secondary rearing in 1989 and 1990, estimated survival rates were greater than 30% one month after release.

Figure 5. Example of Prefectural Farming Fisheries Center (1991), Osaka Fisheries Experimental Research Station, Tanigawa, Osaka Prefecture. Note outdoor tanks for Nannochloropsis *and rotifer culture. Facility includes multispecies spawning tanks and larval rearing tanks (100-300 m^3). Facility also includes outdoor rearing pens and indoor offices and research laboratories. Note seashore tripods and seawall that typifies most of Osaka Bay's intertidal habitats.*

Japan's Fishing Cooperatives

Japan's coastal fisheries are controlled by the Japanese Fishing Cooperative Association. This is a "bottom-up" hierarchical structure that preserves fishing rights and access for traditional family and fishing village units (Kalland 1984). Local fishing cooperatives are the "consumers" of released juvenile crabs, and their input is a principal determinant in prefectural decisions on production levels and release locations. In some instances, fishing cooperatives may levy dues on its members to construct and operate their own hatcheries for *P. trituberculatus* and other species. Fishing cooperatives operate wholesale markets through which all harvested crabs are sold and recorded; therefore, landings statistics are more accurate than records in the Chesapeake Bay and elsewhere, where markets are much more dispersed. — *David Secor*

Predation trials have shown that dragonets (*Repomucenus beniteguri*: Pisces [Perciformes, Callionymidae]) and other crabs are effective predators on C_1-C_3 juvenile crabs that have not yet settled to the bottom (Ariyama 2000). By the C_4 stage, most juveniles have settled out of the water column which, in addition to their larger size (~17 mm CW), contributes to a sharp drop in predation losses (Karakawa 1997). Because extremely high predation losses are expected for C_1 releases, several Japanese scientists believe that prior to 1991, released *P. trituberculatus* juveniles did not significantly contribute to coastal fisheries (Fukada, pers. comm., Ariyama, pers. comm). Since that time, only benthic crabs (C_4-C_5) have been released. For convenience, we refer to these as C_4 juveniles throughout this report.

Secondary rearing from C_1 to C_4 is typically accomplished in large tanks supplemented with complex artificial structure to reduce cannibalism (Figure 6). Secondary rearing methods vary but typically require large-volume rearing systems. Prefectures are also primarily responsible for evaluation of whether released juveniles contribute to local and regional fisheries. The methods that are used to determine post-release survival rates and contribution rates to the fishery are diverse and, in general, poorly developed (see p. 17).

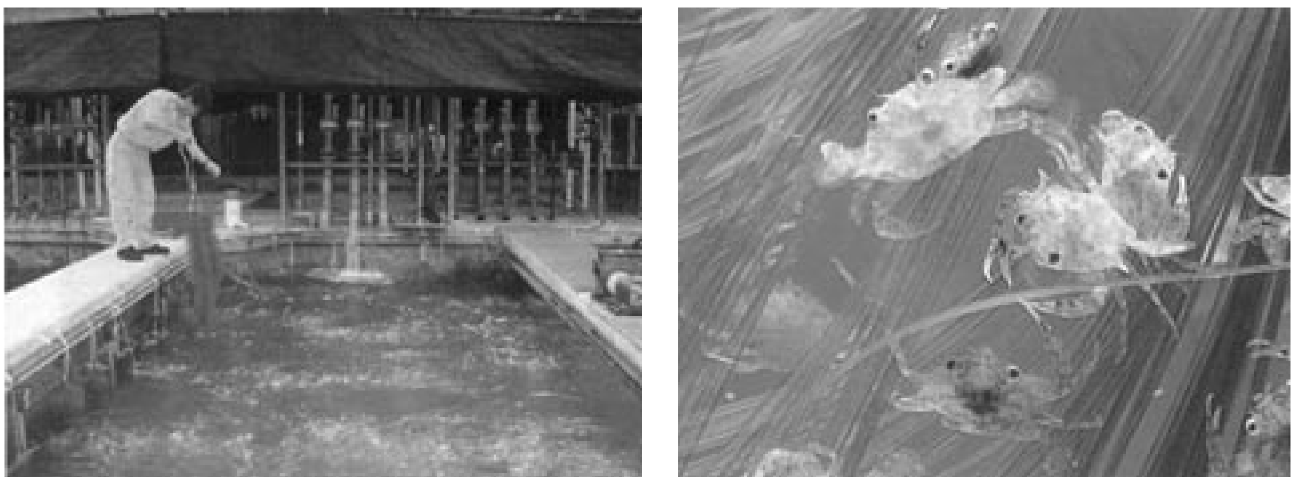

Figure 6. Refuge provided to reduce cannibalism during secondary rearing of juvenile crabs P. trituberculatus*, stages C_1 to C_{3-4} (Osaka Prefectural Farming Fisheries Center). Right panel shows use of structure by juvenile crabs ~5-10 mm CW. This rearing period typically lasts 2-3 weeks. Left photo from Ariyama (2001). Right photo from Japan Sea Farming Association (JASFA).*

Three Case Studies

To clarify Japanese attempts at hatchery-based enhancement for *P. trituberculatus*, three case studies are presented here for systems visited during July 2001. Another limited study is also presented for the portunid crab, *Scylla tranquebarica*, which presented a novel case and method in which hatchery contribution was evaluated. The case studies represent a range of ecosystems, fisheries and methods used to evaluate hatchery-based enhancement (Table 1, Figure 1). The difference in sizes between systems offers an opportunity to improve our understanding of the importance of scale in assessing the effect of hatchery-based enhancement programs for *P. trituberculatus*. Recent research in small systems in Japan has supported the view that hatchery releases may be contributing to swimming crab fisheries that are depressed (Ariyama 2000, Okamoto unpubl ms, Kochi Fisheries Coop. Assoc.). Evidence for successful stock enhancement (i.e., increased population productivity) in all three systems is lacking, and in each of the systems fishing effort remained very high and habitats continued to decline.

▶ Small Enclosed System: Hamana Lake

Hamana Lake is a c. 10,000 hectare coastal lagoon with a single inlet to ocean waters located in Shizuoka Prefecture (Figure 7). Principal nursery and feeding areas are associated with extensive eel grass (*Zostera*) beds within the lagoon; some spawning occurs in this region as well, but most spawning is believed to occur following an emigration out of the narrow inlet into nearshore coastal waters of the Pacific Ocean (Okamoto 2001). Yield of *P. trituberculatus* from the entire system (including adjacent shallow coastal ocean fisheries) is 14 metric tons (t) (Table 1). Harvests of swimming crab occur almost exclusively through "set-nets," a type of pound net. The wings of the set nets are positioned strategically to intercept fishes and crustaceans throughout the lagoon and inlet areas. Because continual harvest by nets in inlet areas could result in overexploitation, there is a regulation to lift nets out of the water for a 12-hr period (3 a.m. to 3 p.m.) each day. Set nets capture a diverse assemblage of species, most of which are brought to market (undersized fishes and crustaceans are released). The minimum size for legal *P. trituberculatus* is 120 mm CW.

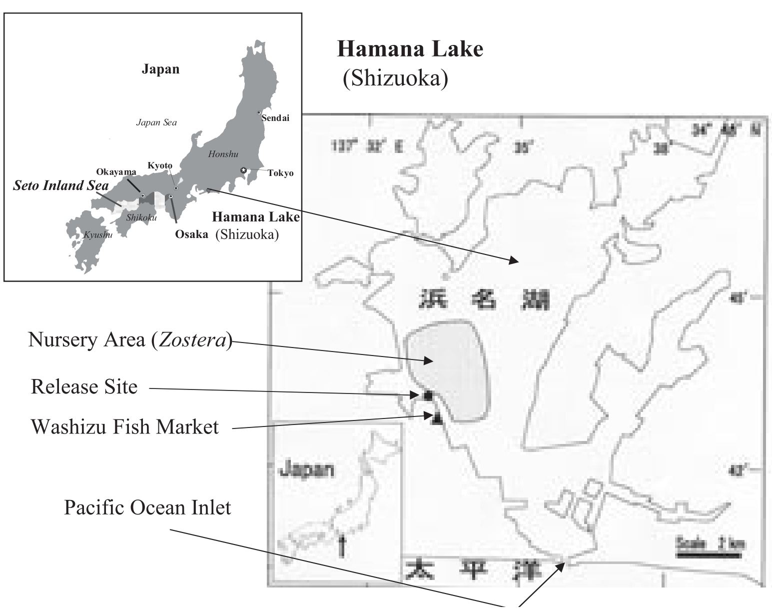

Figure 7. Hamana Lake system (small enclosed system), Shizuoka Prefecture, Japan. Release site and other details pertinent to Okamoto's mark-recapture experiment on P. trituberculatus *are shown. Diagram from Okamoto (2001).*

Although *P. trituberculatus* is the most important crab harvested (~$170,000 per year), nearly a dozen other species of crabs are landed and sold. In 1984, a large decline in yield of *P. trituberculatus* occurred (Figure 8), thought to be the result of a shift in hydraulic conditions that no longer favored transport of coastal-spawned larvae and juveniles through the inlet (Okamoto 2001). In addition, increased shoreline resort and residential development, combined with low flushing rates in some parts of the lagoon, has resulted in increased persistence of hypoxic events that may have reduced system productivity. A program of releasing hatchery-produced crabs was initiated in an effort to compensate for the nearly 10-fold decline in recent harvest levels. Since 1990, approximately 1.4 x 10^6 C_4 crabs have been released annually into Hamana Lake. During the past decade, there has been no corresponding rise in landings with increased numbers of hatchery-released juveniles.

Hamana Lake is the only system for which fishery contribution rate has been examined through mark-recapture methods, one of the most robust approaches for evaluating such rates (see sidebar, Measurement of Hatchery Contribution, p. 17). In June 1998 Dr. K. Okamoto, a Shizuoka Prefecture scientist, released 3,300 C_4 juveniles injected with micro-wire tags into the primary nursery area of Hamana Lake (Okamoto 2001; unpubl. ms). Over the next four months, he undertook a sampling routine of visiting three principal fish markets in regions adjacent to the site of release. Recaptures only occurred for the Washizu Fishing Cooperative, which was immediately adjacent to the site of release (Figure 7). With a sampling rate (number of crabs examined/ number of crabs harvested) of 29%, Okamoto observed 13 crabs that contained micro-wire tags. Based upon the number of crabs examined for tags and tag retention rate (90%), Okamoto calculated a harvest recapture rate (recapture in fishery/number released) of 1.2%.

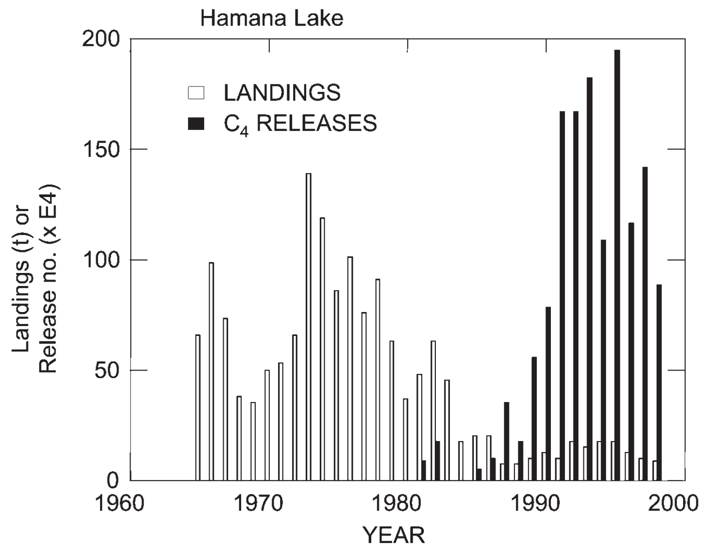

Figure 8. Hamana Lake landings and C4 for P. trituberculatus *releases during the past three decades. Data from Okamoto (2001).*

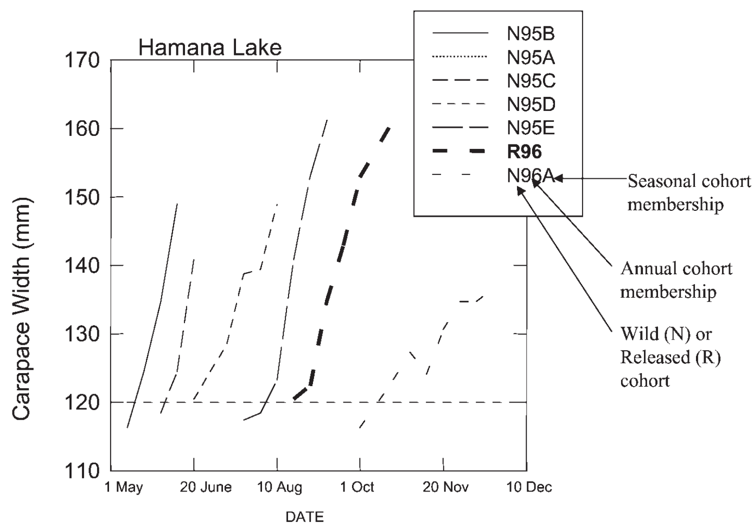

Figure 9. Cohort separation by size analysis for Hamana Lake landings for P. trituberculatus *in 1996. Note entry of the release cohort R96 into the fishery in mid-August and its subsequent growth rate. All other cohorts are designated as natural cohorts. Data from Okamoto (2001).*

A second method more commonly used to evaluate harvest recapture rates is the cohort method, whereby released juveniles occur as a discrete early juvenile cohort of similarly sized crabs. This cohort can sometimes be segregated from wild cohorts through length frequency analysis for 12 to 18 months after release. The cohort approach is supported by early spawn dates of hatchery produced crabs that tend to be 1-2 months earlier than most wild cohorts, and the relatively rapid and consistent growth rates exhibited by

Table 1. Fishery and hatchery statistics for four comparison systems: *P. trituberculatus* in Hamana Lake, Osaka Bay and Okayama Prefecture, and *C. sapidus* in Chesapeake Bay. CW=carapace width, C_x = juvenile crab instar (x); $Harvest_R$ = no. harvested hatchery crabs; $Harvest_T$= total harvest no. $Values based upon July 2001 yen:dollar exchange rates and economic statistics: 100 ¥ = $0.85.

	Hamana Lake	Osaka Bay	Okayama Prefecture	Chesapeake Bay
Gear (% landings)	Set nets (100%)	Small trawls (70%) Set nets (14%) Large trawls (14%) others (2%)	Small trawls (97%) Set nets (3%)	Pots (76%) trot-line (19%) small trawls (scrapes) (0.5%) winter dredge (4%)
Mean landings crabs yr^{-1}	14 tons ('90-98) ~ 67,000 crabs (4.8 crabs/kg for crabs > 120 mm CW; Ariyama 2000)	57 t ('90-98) ~ 353,000 crabs (6.2 crabs/kg for crabs >100 mm CW; Ariyama 2000)	145 t ('90-97) ~ 696,000 crabs (4.8 crabs/kg for crabs > 130 mm CW; Ariyama 2000)	36,000 t ('90-'99) ~ 190,000,000 crabs (5.5 crabs/kg; CBSAC statistics)
Value yr^{-1}	$171,000 ($2.40/crab; pers. obs)	$1,425,000 ($25/kg - Ariyama 2000)	$1,775,000 ($2.40/crab; pers. obs.)	$43,000,000 (hardshell - NOAA 2000 statistics)
Number of fishers	400	200	-	>1000
Size limits (2001)	Size limit=120 mm CW	None; recommended size limit=120 mm CW	Size limit=130 mm CW No ripe females	Size limit=127 mm CW (hard) Size limit=76 mm CW (soft) No size limit for winter dredge fishery (VA)
Season limits	None	None	None	May - November
Weekly/daily limits	Limited Entry (Fishing Cooperatives) 3 pm - 3 am soaks	Limited Entry (Fishing Cooperatives)	Limited Entry (Fishing Cooperatives)	Quasi-limited Entry (licenses), pot number and soak limits
Fishing Mortality Rate	-	4.39 yr^{-1} (~ 99% yr^{-1})	-	0.9 yr^{-1} (~ 60% yr^{-1})
Age at entry (wild)	0.4-1.0 yrs	0.4 - 1.0 yrs (120 mm CW)	0.4 - 1.0 yrs	1 - 1.5 yrs (hard) <0.5 - 1.5 yrs (soft)
Age at entry (hatchery)	0.4 - 0.5 yrs (120 mm CW)	0.3 - 0.4 yrs (~ 100 mm CW)	0.4 - 0.5 yrs (130 mm CW)	
Product value (retail)	Softshell ea <$1.00 (not desired) 120-150 mm CW; ea ~ $3.40 160-200 mm CW; ea ~ $5.10 >200 mm CW; ea ~ $8.50	softshell ea < $1 (not desired) <120 mm CW; doz ~ $23.00 120-150 mm CW; ea ~ $3.40 160-200 mm CW; ea ~ $8.00 >200 mm CW; ea ~ $14.00	softshell ea < $1 (not desired) 120-150 mm CW; ea ~ $3.40 160-200 mm CW; ea ~ $5.10 >200 mm CW; ea ~ $8.50	softshell ea ~ $3 120-130 mm CW; doz ~ $8 females (<150 mm CW; doz ~$8 140-160 mm CW; doz ~ $14 >160 mm CW: doz ~ $20

Table 1 continued.

	Hamana Lake	**Osaka Bay**	**Okayama Prefecture**	**Chesapeake Bay**
Hatchery releases yr^{-1}	1.4 x 10^6 C_3-C_4 ('90-98)	0.7 x 10^6 C_3-C_4 ('92-98)	1.1 x 10^6 C_3-C_4 ('91-93)	
Method of 2° rearing	Tanks	Tanks with structure	Coastal impoundments	
Method of release	Single site, single release time, *Zostera* beds	multiple sites, multiple months, sandy intertidal beaches, macroalgal *Gracilaria* beds	multiple sites, multiple months, *Zostera* beds	
Harvest Recapture Rate ($Harvest_R$ /Release No.)	1.2% (mark-recapture - '98) 0.85% (cohort '92-98)	31.3% (modeling approach '90)	5.7% (hatchery anomaly of chelae)	
Contribution rate (yr^{-1}) ($Harvest_R$ /$Harvest_T$)	18% (cohort analysis '92-98)	59% (modeling approach '90)	9% (cohort analysis '98)	
Method(s) for determining contribution rates	Mark-recapture ('98) Cohort analysis ('92-'98)	Post-release and harvest model ('90)	Cohort analysis (every yr) hatchery anomaly of chelae ('98)	
Estimated value to fishery (contribution x harvest value)	\$31,000	\$910,000	\$160,000	

both wild and hatchery cohorts (in comparison to blue crabs) (Figure 9). The approach is particularly valuable when there is a single spring season of hatchery production and early summer release, rather than several cycles of production and release during the entire summer. The former situation exists for Hamana Lake, facilitating cohort identification. Okamoto used the lengths of recaptured crabs to verify his cohort interpretations (Figure 10). In general, lengths of recaptured crabs were contained within modes attributed to hatchery releases. Using the cohort analysis approach during the period 1992-1998, Okamoto predicted annual harvest recapture rates between 0.3% and 2.2%. Based upon a mean harvest recapture rate of 0.85%, then fishery contribution rate was estimated as 18% (see Table 1, harvest recapture rate, (0.0085) * release number (1.4 $10^{6)}$ / harvest number (67,000)).

The small number of returned micro-wire tags in Okamoto's study conveys considerable uncertainty to the study. Micro-wire tags are sometimes difficult to detect (detection occurs through use of an electronic magnetic "wand"), and if only 6 additional tagged crabs were undetected, then the estimate of the contribution to the fishery would increase by ca. 50%. Still, the cohort and tagging analyses were in good agreement with each other, suggesting that contribution rates were moderate in Hamana Lake.

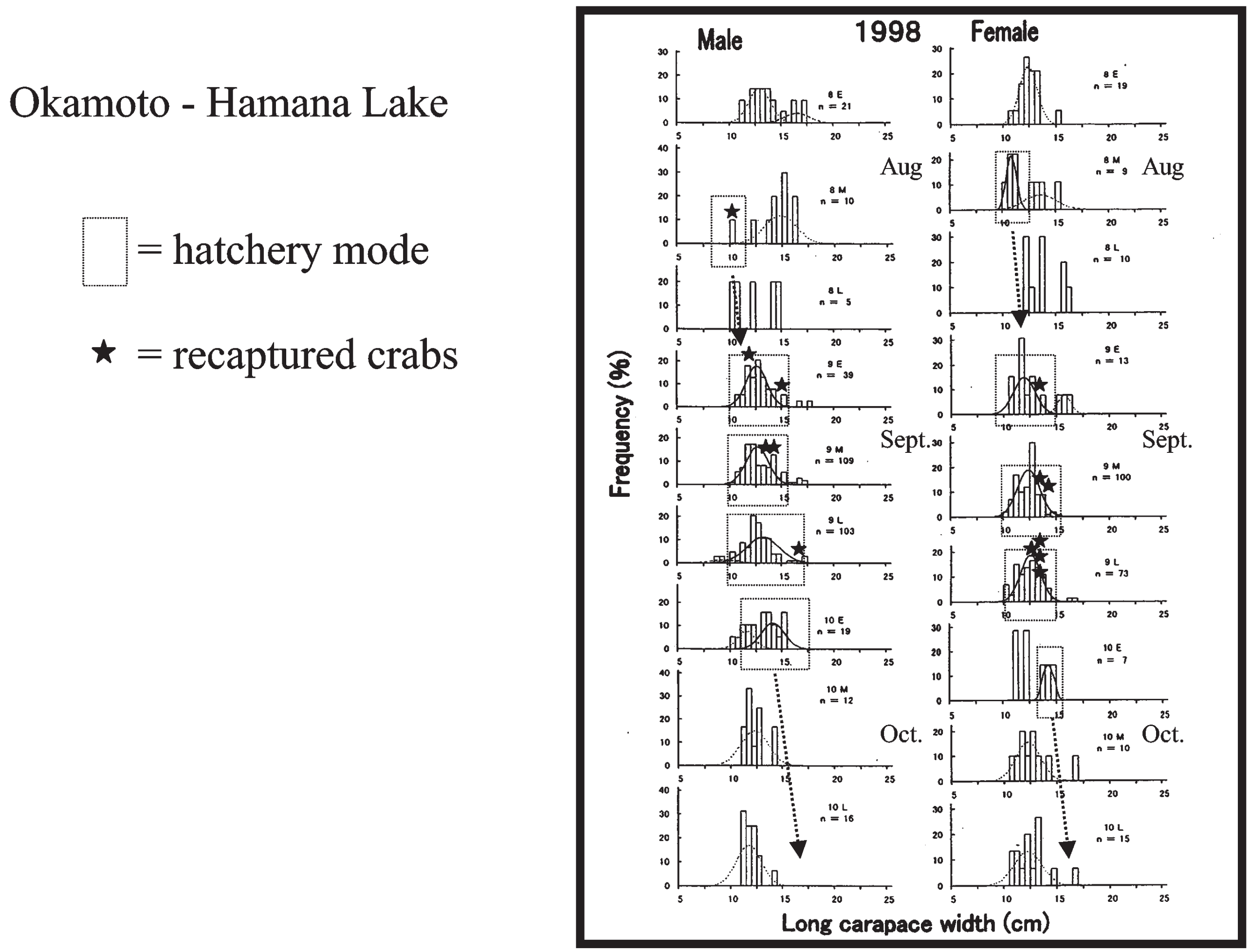

Figure 10. Cohort separation by size analysis for Hamana Lake landings of P. trituberculatus *in 1998. The hatchery cohort is designated by a box and its seasonal progression is designated by an arrow. Stars indicate released crabs (n=13) recaptured by Okamoto at the Washizu Fish Market. Data and diagram from Okamoto (2000).*

Applications of Population Genetics to Assess Survivorship of Hatchery-Reared Crabs

The Japanese Sea Ranching Program has also completed successful large scale rearing of other portunid crab species, including the *Scylla tranquebarica* (mangrove crab), which, like *Portunus trituberculatus*, is primarily fished from August to October (Figure 11). A recent population genetics study of *S. tranquebarica* released in Urado Bay, a small semi-enclosed bay in southern Shikoku (Figure 1), provides a test of whether hatchery-reared portunid crabs may survive and grow to contribute to the reproductive stock of a sub-population (Kochi Fisheries Cooperative Association,Yokohama Branch). The study used mitochondrial restriction length polymorphism (mtDNA) haplotypes as an inherent, maternally inherited DNA marker that can be followed in progeny. A stock enhancement program was initiated in 1986 and reached a peak stocking level of nearly 200,000 C_2 instar crabs in 1997. In 1995 and 1996, mtDNA haplotypes in the natural population and hatchery-reared crabs were determined. Nine major haplotypes were found in the natural population. In 1997, one haplotype (Type 2) was selected for propagation and release into Urado Bay. From analysis of a statistically appropriate sample size of 500 mature crabs (Kishino et al. 1994), the Type 2 haplotype accounted for 29% of the mtDNA genotypes. Based upon baseline Type 2 haplotype frequencies observed for 1995 and 1996, the authors estimated that 17% of the stocked individuals survived to join the reproductive stock. This estimate assumed that the Type 2 haplotype frequency in the natural population remained invariant between 1995-1997. Karakawa attempted to use mtDNA haplotypes to distinguish hatchery reared *P. trituberculatus* from wild stocks in Okayama Prefecture. Fourteen distinct *P. trituberculatus* haplotypes were found in the wild population (ranging from 44.2% to 1.1% in frequency). They chose haplotype Type 5 (4.2% frequency) as their founder stock for release. Upon subsequent recapture, they saw no change in haplotype Type 5 frequency in caught crabs, which they interpreted as being due to the low frequency of the founder stock haplotype in the wild population (should be > 20%). Although this study was not definitive, it does emphasize that the approach is widely applicable.

— *Allen Place*

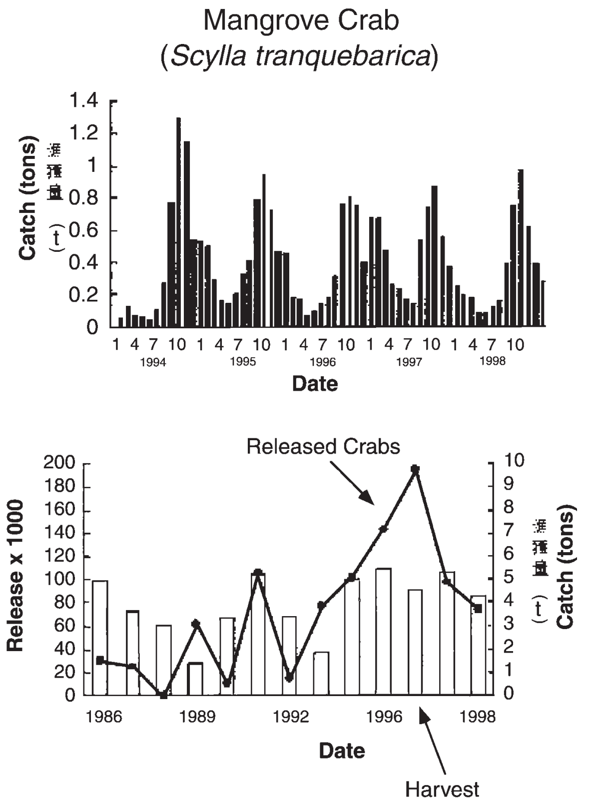

Figure 11. Catch and hatchery release information for mangrove crab in Urado Bay (Figure 1, Shikoku Island, Japan). MtDNA markers indicate that released crabs have made contributions to the overall gene pool of the Urado Bay population. See text for details.

▸ Heavily Impacted System: Osaka Bay

Osaka Bay (Figure 12) is a highly urbanized and industrialized system heavily impacted by continuing development of shorelines, most recently in association with the construction of the Kansai International Airport. Principal nursery grounds occur in shallow sub-tidal regions on the eastern and northern parts of the bay, including Osaka Harbor itself (Ariyama 2000). Summertime hypoxia (< 1 mg/L dissolved oxygen) results in seasonal absence of juvenile crabs in the Harbor that are otherwise relatively abundant during early summer and fall/winter months (Ariyama 2000). Spawning occurs throughout Osaka Bay during summer months. The principal gear used is the Ishigeta dredge (Figure 13), a small 1.5 m wide trawl that contains a toothed dredge, similar to a Virginia winter dredge (Table 1). A small fishing vessel tows four of these simultaneously, and trawls bring up a diverse assemblage of shellfish, fishes and crustaceans. Other gears that land swimming crabs include set nets and other trawl types. The exploitation rates for the Ishigeta dredge is estimated to be extremely high (see below) and as opposed to other prefectures, no size limit is enforced, although a minimum size of 120 mm CW is encouraged. A visit to a retail market confirmed that crabs <100 mm CW are commonly harvested and marketed. The values for swimming crabs in Osaka region ($25/kg) seem to be slightly higher than other regions in Japan (Table 1), resulting in an important urban fishery (Ariyama 2000). During 1990-1998, average annual fishery yield and value were 57 t and ~$1.4 million, respectively. The fishery underwent two abrupt cycles of decline in the 1960s and 1980s (Figure 14), which are believed to be the result of loss of sandy nursery habitat through shoreline development (Figure 15), poor water quality, and perhaps increased exploitation (Ariyama 2000). Since 1992, Osaka Prefecture has released an average of c. 0.7 x 10^6 C_{3-4} juveniles each year to mitigate against reduced harvests (Ariyama 2000; Figure 14). Landings data give no indication that hatchery releases have resulted in improved fishery yields.

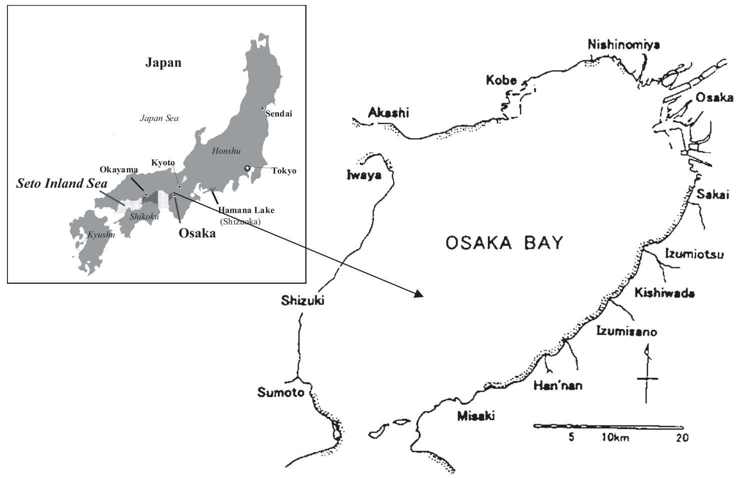

Figure 12. Osaka Bay system (heavily impacted system), Osaka Prefecture Japan. Diagram from Ariyama (2000).

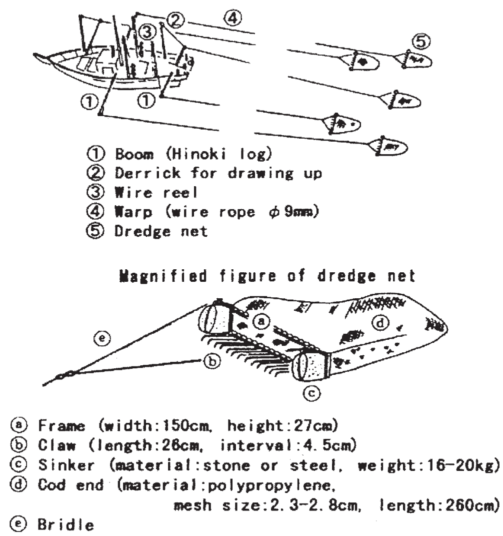

Figure 13. Ishigeta dredge diagram. The dredge is the principal gear used in Osaka Bay and Okayama Prefecture fisheries. In Hamana Lake, crabs are taken with a set net (not shown). Diagram from Ariyama (2000).

In the early 1990s, Dr. H. Ariyama, an Osaka Prefecture scientist, evaluated secondary rearing and rates of post-release survival, and conducted extensive research on fishery contribution. As discussed previously, this research showed that C_1-C_3 stage crabs were highly vulnerable to predation and cannibalism in the field due to their pelagic behavior. He concluded that semi-natural secondary rearing systems should favor post-release survival. In 1990, Ariyama carefully reared C_1-C_4 juveniles in net pens and then released 246,000 C_4 crabs in a semi-contained region of sandy beach habitat. Over the following two months, he intensively sampled this and adjacent regions to monitor dispersal. From this release trial, Ariyama observed that juvenile crabs began dispersing into the adjacent regions one month after release (C_7-C_9 crab instars), and by 6 weeks (C_9-C_{10} instars; c. 67 mm CW) most released crabs had dispersed from the region into which they were released. Ariyama measured a 66% decline in abundance in the release region and adjacent regions over the first ~4 weeks (Figure 16). Assuming that net dispersal into (by natural crabs) and out of (by released crabs) the study area was zero, Ariyama used 34% survival as a benchmark survival rate for released C_4 crabs to harvestable size (c. 80-90 mm CW). This study also confirmed that released crabs could grow rapidly and enter fisheries by late summer/early fall, during their first year of life.

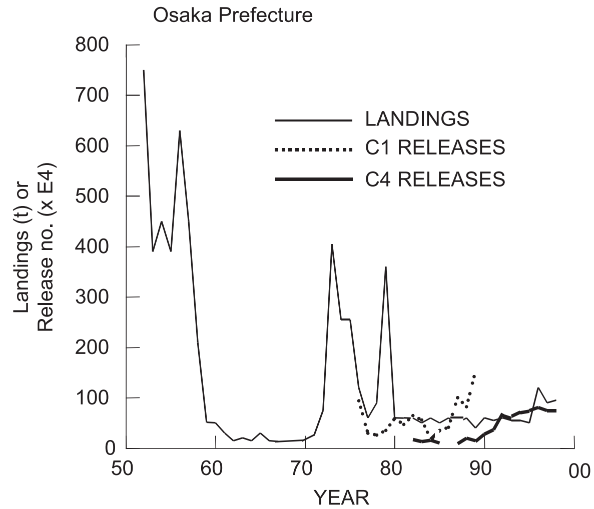

Figure 14. Osaka Prefecture landings and C_1 and C_4 releases of P. trituberculatus *during the past four decades. Note fishery crashes in 1959 and 1980. Data from Ariyana (2000).*

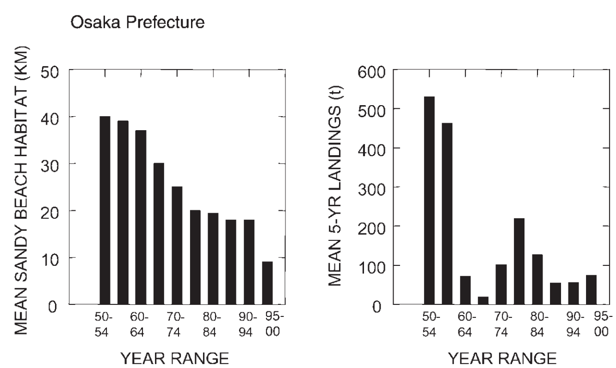

Figure 15. Five-year average beach habitat perimeter (left panel) and 5-year landings of P. trituberculatus *(right panel) in Osaka Prefecture during the past four decades. Note 4-5 fold decline in both beach habitat and landings over this period. Data from Ariyama (2000).*

To estimate harvest recapture rate, Ariyama (2000) used a modeling approach (see sidebar, Measurement of Hatchery Contribution, p. 17), rather than direct evidence of hatchery crabs taken in the catch. He coupled his post-release survival rate (34%) with a harvest model for *P. trituberculatus* in Osaka Bay. The post-release survival rate represented the fraction of released crabs that entered the fishery. The harvest model represented the fraction of hatchery crabs that were subsequently caught. The harvest model was based upon the standard yield equation

$$C = R \left[\frac{F}{F + M} \left(1 - e^{-(F+M)} \right) \right] \quad (1)$$

where C is yield in the fishery, R is the abundance of the hatchery cohort at entry into the fishery, F is instantaneous mortality due to fishing, and M is instantaneous mortality due to natural causes (Gulland 1983). The time step over which mortality rates are tallied can vary according to what data are available just as long as instantaneous rates correspond to that time step. Ariyama chose a monthly time step for his model, which permitted him to track the hatchery cohort through seasonal changes in fishing effort. Natural mortality (M) was available from a previous tagging study (Kitada and Shiota 1990). To estimate F, Ariyama first determined the daily efficiency (q) with which an average fishing vessel extracted individuals from the population (Delury method; Hilborn and Walters 1992). The product of this coefficient and effort (number of fishing vessels x days) provided monthly estimates of F.

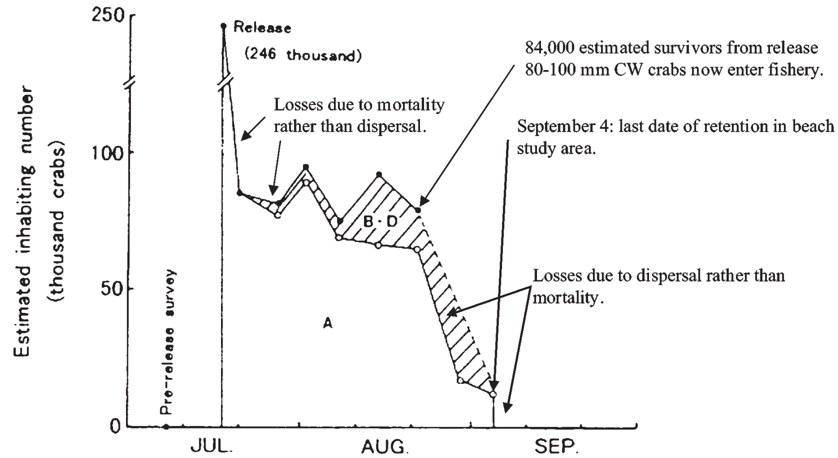

Figure 16. Post-release survival of C_4 juvenile P. trituberculatus *in semi-enclosed beach habitat in Osaka Bay system, 1990 (data and diagram from Ariyama 2000). Beach "A" refers to beach where 246,000 juveniles were released. Some crabs subsequently dispersed to beaches "B," "C," and "D" and these are shown by hatched area. After sampling on September 4, Ariyama assumed that dispersal became dominant in the rate of loss in abundance observed in the four beach areas. To estimate survival until September 4, Ariyama combined estimated abundances in all beaches for that date.*

Using estimates of F and M, Ariyama calculated monthly yields for the 1990 cohort of 84,000 hatchery crabs expected to recruit into the fishery at the beginning of September. Monthly natural mortality was estimated at 4.6%, excluding months December to April, when mortality was assumed to be negligible. Monthly fishing mortality rates were estimated to range from 19% (January) to 46% (August), which suggests an exploitation rate considerably higher than that observed in other systems (e.g., on an annual basis, >90% of crabs in Osaka Bay are harvested compared with c. ~60% annual removal rates for Chesapeake Bay blue crabs). The harvest model predicted that 76,324 of the released crabs were harvested (91% harvest recapture rate) during their first year in the fishery; another 7014 crabs died of natural causes, and the remaining 662 crabs persisted into the next year of the fishery. Ariyama (2000) predicted that most released crabs (65%) were harvested within three months after entering the fishery. The high exploitation rates translated into harvest recapture rates of 31.3%. This in turn resulted in a relatively high fishery contribution of 59% for 1990 landings. See Table 1, harvest recapture rate, (0.313) * release number (0.7×10^6) / harvest number (372,000).

Osaka Prefecture releases $C_{3\text{-}4}$ crabs throughout the summer, which precluded a size-based analysis of hatchery cohorts similar to those conducted for Hamana Lake. Currently, there is an active research program at Osaka Fisheries Experimental Station to develop tagging methods to support estimates of the hatchery contribution rate for *P. trituberculatus* and other crustaceans (Ariyama et al. 2001). Such studies are quite important because they will provide initial physical evidence of hatchery-produced crabs in the fishery, and thereby test Ariyama's post-release survival and harvest models.

▸ Larger, Open System: Okayama Prefecture (Seto Inland Sea)

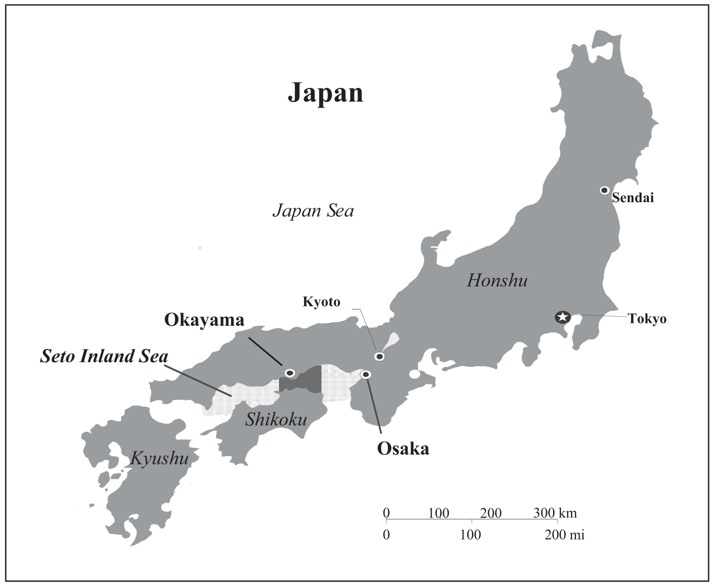

Figure 17. Okayama Prefecture portion of Seto Inland Sea (open system), Japan.

Coastal waters of Okayama Prefecture (Figure 17) occupy a relatively small segment of the Seto Inland Sea[1] between Honshu and Shikoko Islands, but support a larger *P. trituberculatus* resource (145 t) than Hamana Lake or Osaka Bay (Table 1). Similar to Osaka Bay, the principal gear used is the Ishigeta trawl. Since 1990, Okayama Prefecture has released ~ 1 X 10^6 C_4 juveniles each year (Figure 18; data on releases after 1993 are not shown but have continued at a nearly constant level during most of the last decade [Fukuda, pers. comm.]). Higher releases of C_1 juveniles occurred prior to 1991 and were apparently coincident with higher landings, but prefectural scientists believed that any correlation was unrelated to hatchery releases because large releases of C_1 instars were unlikely to result in improvements of catch (Fukuda and Karakawa pers. comm; also, see above references to experimental work by Karakawa 1997 and Ariyama 2000). The correlation in patterns between release number and catch is mostly driven by three high release years (1981-1983), where more than 2 million C_1 crabs were released. Particularly curious is the cycle of hatchery releases. Typically, hatchery releases are relatively stable, determined by careful planning by the prefecture. Japanese scientists could offer no explanation for the apparent correlation between historical landings and releases of C_1 juveniles. During this past decade, landings have undergone an oscillation and are now at low levels (88 t in 1999). Release levels have been maintained at approximately 1 million C_4 juveniles during this period (Fukuda, pers. comm).

Secondary rearing in Okayama occurs in 0.8 ha coastal impoundments that are also used for secondary rearing of Japanese prawn and juvenile marine fishes. The impoundments are large excavations in coastal areas, contained in part by sea walls. The Yorishima Secondary Rearing Center was constructed at a cost of $2.4 million (Ariyama 2001). Sand bottoms are thought to allow juveniles to acclimate to natural conditions and reduce cannibalism. Harvesting C_4-C_5 crabs after 15 days of rearing from the C_1 instar stage is accomplished by tidal flow out of the impoundment and a catchment basin. Three days of tidal out-flow are required to collect all crabs. Although expensive, Ariyama and other scientists interviewed believed that this method of secondary rearing was optimal because it substantially reduced cannibalism and favored post-release survival.

Dr. J. Karakawa (Okayama Prefectural Scientist) has used the size-based cohort method to estimate harvest recapture rates. This procedure is complicated and uncertain because two large releases occur each year that must be separated from each other and from wild cohorts. In an effort to verify the identification of hatchery cohorts, Karakawa developed an index of anomalous chela (claw) symmetry that was associated with loss of this limb during the hatchery collection of C_4 crabs, and subsequent regeneration. The anomaly was

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[1] The Seto Inland Sea in its entirety supports an annual *P. trituberculatus* yield of 1800 t or c. \$38 x 10^6.

observed in approximately 6% of landed crabs and this rate was attributed to hatchery individuals (Karakawa 2001). The anomaly was frequently observed to coincide with hatchery cohorts identified through length frequency analysis, although the anomaly appeared to occur at equal frequency for all sized crabs for any monthly sample (Figure 19). Further, the rate of natural chelae loss (autotomy) is not reported quantitatively but stated to be negligible (Karakawa pers. comm.). Autotomy rates observed for *C. sapidus* in the Chesapeake may be much higher (ca. 25%; Smith and Hines 1991). Based upon the 5.7% harvest recapture rate (measured using the cohort approach), the fishery contribution rate for 1998 was 9% (harvest recapture rate (1998: 0.057) * release number (1998: 1.1 10^6) / harvest number (1998: 716,000)).

To evaluate migration and habitat use patterns by hatchery-produced and wild *P. trituberculatus*, Okayama Prefectural scientists recently released marked juvenile crabs (~80 mm CW) at two sites and recaptured them over a two-year period (Karakawa 2001). Marked crabs initially occurred in shallow regions near the release site, then dispersed to deeper areas offshore to overwinter, and then returned to shallow nearshore areas to spawn the next year. These behaviors are similar to those of wild *P. trituberculatus* (Karakawa 1999). Two years after release, the scientific monitoring program recaptured 20-30% of released crabs (rates varied by release group). Importantly, all tagged crabs were recaptured within 20 km of the release sites; the majority were recaptured within 5 km of release sites.

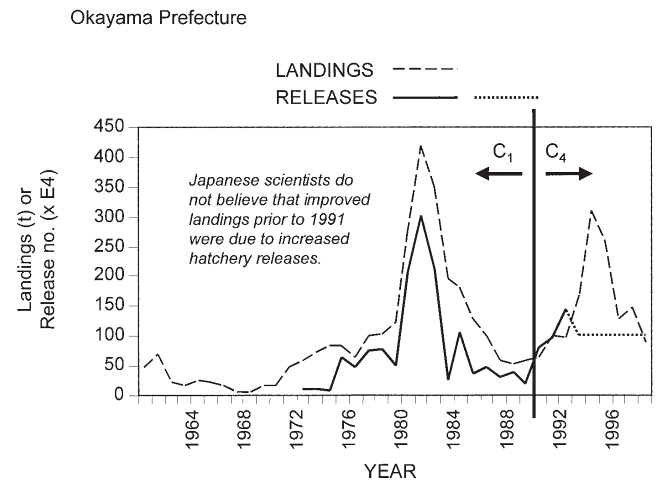

*Figure 18. Okayama Prefecture landings and C_1, C_4 hatchery crab (*P. trituberculatus*) releases during the past three decades. Note that despite coincident trends in landings and release numbers for C_1 crabs, Japanese scientists do not believe that increased landings were due to hatchery-based enhancement. Data from Karakawa (2001). Release levels have been maintained at approximately 1 million C_4 crabs from 1993 to 2000 (dotted line; Fukuda, pers. comm.).*

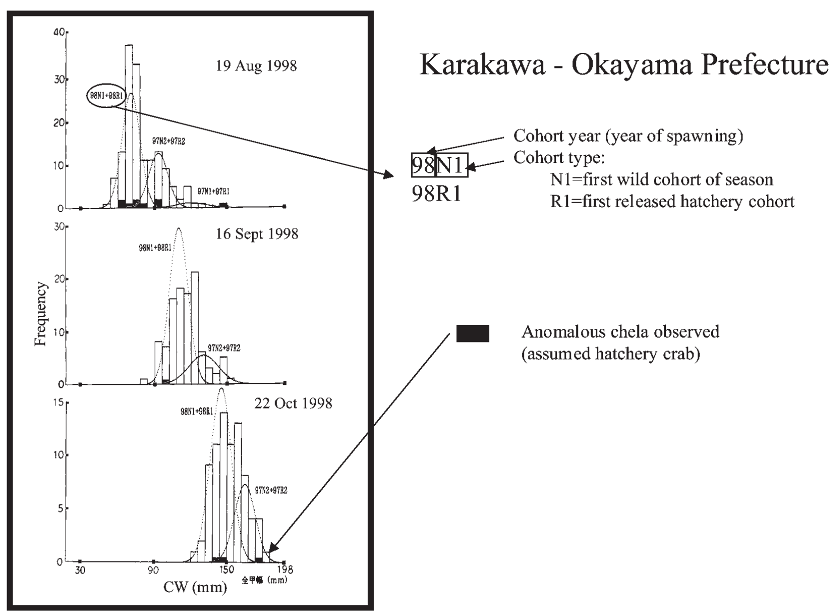

Figure 19. Cohort separation by size analysis for Okayama Prefecture landings of P. trituberculatus *in 1998. Modes are fitted to length frequency data. The distribution of crabs exhibiting anomalous chelae and assumed to be of hatchery origin is shown. Data and diagram from Karakawa (2001).*

Summary of Case Studies

Case study systems ranged considerably in physical size, geomorphology, fishery yield and estimates of recapture rates of hatchery released crabs. Still, similarities existed in the number of released crabs each year and the methods used to produce those crabs. In all three systems and in other Prefectures in Japan, there was an important shift in the early 1990s from releases dominated by C_1 instars to releases of C_4-C_5 instars. Research by Ariyama (2000) and Karakawa (1997a) indicated that releases of the smaller pelagic C_1 crabs during the period 1973-1990 were largely ineffective in enhancement of fishery resources. Thus, analysis of hatchery contribution rates has been limited to the last decade.

Because release levels tend to be constant (set by prefectural quotas) there are only minimal ranges within which to contrast landings data. However, for the recent period of C_4 releases, there was no apparent correlation between number of crabs released and increased harvest levels in any of the case study systems. Still, lack of any apparent correlation between release and harvest levels does not imply that hatchery crabs are not contributing to fisheries. Patterns in landings are more likely driven by ecosystem-level changes. Hamana Lake and Osaka Bay have both undergone fishery crashes from 1980 levels and low harvests have persisted throughout the last decade. Landings in Okayama Prefectural coastal waters show decadal oscillations, which suggest that climate or oceanographic factors affect *P. trituberculatus* yields. Under the assumption that hatchery enhancement has been implemented with crabs of sufficient size only after 1990, it is apparent that hatchery releases have done little to restore these fisheries to historical levels.

On the other hand, hatchery releases into Hamana Lake and Osaka Bay may be contributing to sustaining low catch levels, and subsidizing the reduced reproductive stock of crabs. In support of this view, recent research in the smaller of the systems visited (Hamana Lake and Osaka Bay) indicated that that hatchery-released crabs were contributing to fisheries (Ariyama 2000, Okamoto unpubl ms, Kochi Fisheries Coop. Assoc.), while evidence for fishery enhancement in the larger system (Okayama Prefecture) was insufficient to make this determination.

Predicted harvest recapture rate was much higher for Osaka Bay than for Hamana Lake, Urado Bay, or Okayama Prefecture (Table 1), and because no physical evidence is yet available on harvest contribution rates, model assumptions need to be carefully considered. While exploitation rates for Osaka Bay are believed to be quite high, uncertainty remains regarding the calculation of the actual rates. The Delury method used for estimating fishing efficiency (q) was conducted during cold weather months (December-April) when crabs are more easily captured. This could have inflated estimates of q and fishing mortality rate (F). Still, given the rapid growth and relatively high survival of the released crabs in Ariyama's 1990 study, there seems a strong possibility that hatchery releases are making significant contributions to harvests in Osaka Bay. Post-release survival estimates for Osaka Bay were based upon a single study (1990) in which secondary rearing and release conditions may have been substantially improved over those that occur using routine prefectural practices. In particular, leg loss during collection of tank-reared C_4 instars is believed to contribute to early mortality of released crabs. Ariyama (2000) conducted a similar study in 1982 on post-release survival but for this study, secondary rearing was conducted in cement tanks (the more typical prefectural practice), rather than net pens. Survival during the first month after release of C_3-C_4 juveniles was only 2%. A clear conclusion from this case was that the method of collecting and handling hatchery-produced juvenile crabs for transportation and release can have negative consequences. Highly concentrated batches of juvenile crabs can lead to significant limb loss that in turn will reduce survival of released crabs.

These results emphasize the importance of detailed assessment and analysis of factors affecting successful survival of released juveniles. Though we have highlighted the research of several prefectural scientists who are active in developing quantitative evidence for the assessment of hatchery enhancement, in general such research is nascent and is greatly underfunded relative to the investment in hatchery production. There remain many untested fundamental assumptions in the methods used to evaluate harvest recapture rates, and we should attribute high uncertainty levels to these rates (Table 1). Particularly valuable in the future evaluation of hatchery contribution will be recent developments in tagging crabs with micro-wire tags and more conventional external tags (Okamoto 1999; Ariyama et al. 2001). Also, more experimental approaches, such as those utilized by Dr. Okamoto in Hamana Lake, will substantially advance evaluations of how hatchery released crabs contribute to fisheries, and how they interact with wild *P. trituberculatus* and potentially affect the ecosystems into which they are released. As another example of nascent research, the mtDNA study of *Scylla tranquebarica* (see sidebar, Applications of Population Genetics to Assess Survivorship of Hatchery-Reared Crabs on p. 25) also indicated that hatchery releases could make local contributions to populations of a retentive crab species. Genetic markers should be very useful in the future evaluation of scientific approaches in *P. trituberculatus* as well. These examples of scientific approaches in evaluating the effectiveness of hatchery-based enhancement (see p. 15, Goal 6), while promising, are still embryonic and in need of substantially increased support by government entities, should they be successful. We re-emphasize a central point here: within the Japanese Sea Ranching Program, there has been little scientific evaluation of effectiveness of mass releases of swimming crabs and other species despite its 30-year existence.

Implications for Chesapeake Bay Blue Crab Enhancement

In Japan and elsewhere, public and fisher perceptions often cause government agencies to place production demands over goals related to scientific evaluation of fisheries enhancement. For instance, consider a relatively simple experiment to evaluate enhancement by only releasing *P. trituberculatus* in alternate years. Given the rapid recruitment of hatchery-released *P. trituberculatus* to the fishery, this type of experiment should be effective in evaluating whether release years result in higher yields than non-release years. But consider a fisher or taxpayer's perspective: what is the benefit of not releasing crabs for half the years of a given period? The emphasis on production is also clearly seen in the initial goals put forth by the Japan Sea Ranching Program, which emphasize production of larvae and young juveniles and then sequentially move towards evaluation of hatchery contribution. This may seem like a logical series, but recall that most development of juvenile production for *P. trituberculatus* occurred over two decades ago. Rather than developing means with which to quantitatively evaluate hatchery releases, national and prefectural centers have instead emphasized research on mass production of other more difficult species such as squid, grouper, eel, and bluefin tuna. Thus, production science is substantially advanced, but scientific evaluations of hatchery-based enhancement remain underdeveloped. The jeopardy in not simultaneously considering the series of objectives necessary for hatchery enhancement is apparent in lack of evaluation of the stage at release for *P. trituberculatus* (i.e., C_1 vs. C_4) during the 1970s and 1980s, which arguably resulted in many years of wasted effort in trying to enhance Japanese crab fisheries. Such criticisms similarly apply to hatchery programs elsewhere in the world, where enhancement tactics and goals are incompletely considered despite large public investments (Solemdal et al. 1984; Secor and Houde 1998; Lichatowich 1999; Hilborn and Eggers 2000; Secor et al. 2000a).

In applying lessons from the Japanese case studies to hatchery-based enhancement in the Chesapeake Bay, the authors diverged in opinion on the feasibility of hatchery-based enhancement. In part, this was driven by the manner in which the disciplines of fisheries science, ecology, and aquaculture diverge on uncertainty in stock enhancement evaluation in Japan and elsewhere. D. Secor believes that sufficient information and perspective can be drawn from the Japan case studies to make the judgment that stock enhancement is not a desirable goal in the management of Chesapeake Bay blue crabs. A. Hines and A. Place believe that additional scientific investigations are needed to evaluate feasibility issues. Points of important agreement were reached on the merits of continued research on the artificial propagation of crabs, which will contribute valuable information on reproductive physiology, and through release experiments of juvenile crabs to support habitat and fishery management aims, as well as to provide a means to begin to evaluate the feasibility of stock enhancement.

▸ Artificial Propagation and Chesapeake Bay Blue Crabs

D.H. Secor

Differences in the life cycle and relative productivity between Chesapeake Bay blue crab and Japanese *P. trituberculatus* are substantial and informative in evaluating the issue of hatchery enhancement. The yield and value of the Chesapeake Bay blue crab fishery is two to three orders of magnitude greater than those case studies developed for *P. trituberculatus*. Fishery independent studies on *P. trituberculatus* indicate relatively short distances (<30 km) between spawning, nursery, and feeding areas for a given *P. trituberculatus* stock (Ariyama 2000; Karakawa 2001). In a two-year mark-recapture study, Karakawa (2001) released 80 mm CW crabs into the Seto Inland Sea and subsequently recovered tagged crabs within 20 km of their release location. In contrast, female blue crabs that occur in the Maryland waters must undertake migrations that range between 110 km (mouth of the Potomac) and 300 km (head of the Bay) to marine waters to spawn. Similarly, juveniles that occur in the upper bay all originate from marine waters outside the Chesapeake Bay. Therefore, while hatchery contribution in Japan can be examined on a local scale (lagoon, embayment, segment of Inland Sea), the Chesapeake Bay must be considered on an ecosystem-wide basis. Given this essential difference in scale, one is forced to conclude that it is infeasible to supplement Chesapeake Bay's productive and large fishery.

For the sake of example, I utilized harvest recapture rates from the Japanese case studies and predicted how many C_4 crabs would be required to supplement by 10% a depressed yield of Chesapeake blue crabs (100 million crabs; c. 50% current level) (Table 2). Estimates ranged from 100 million to 1 billion juveniles! (The Osaka Bay estimate of harvest recapture rate was excluded since it was driven by extremely high harvest rate — 92% per year — which was two times that predicted for the Chesapeake Bay — 47% per year.) I also applied a simple model of early juvenile mortality (Miller 2001) together with a harvest model (equation 1) specific to Chesapeake Bay blue crab. Again, hundreds of millions to billions of released C_4 juveniles would be required to make only small contributions (10%) to a depressed Chesapeake stock. As a reminder, current levels of C_4 juvenile production for all of Japan, which leads the world in production of juveniles (involvement of 18 prefectural centers and 1 national station), is 28-42 million per year (Ariyama 2000). In summary, the manager of Japan's single largest *P. trituberculatus* hatchery (Tamano National Station) was correct in his reaction to the idea of hatchery enhancement in the Chesapeake Bay: "It is very difficult to go against such a large catch!" (K. Maruyama, Director, Tamano Station, Japan Sea-Farming Association, Okayama pers. comm.).

That Japan has carried on a stock enhancement program for more than 20 years without clear evidence of its effectiveness at first blush seems remarkable. On the other hand, there are few systems in the world for which stock enhancement has been shown definitively. Lack of evidence for stock enhancement in Japan and elsewhere lies with inadequate science, but of equal importance is the amount information and uncer-

Table 2. Scenarios of Chesapeake Bay stock supplementation for a depressed stock of blue crabs (harvest level 100 million individuals), based upon survival of released juveniles and harvest rates. Post-release survival of C_4 crabs was estimated according to Miller (2001) who used Peterson and Wroblewski's (1984) size-dependent mortality model to estimate post-settlement and juvenile mortality rates. The C_1 - C_4 period must be decremented from this mortality rate. Because the duration of this period in the wild is uncertain (in hatcheries, the duration is less than 30 days), three duration levels were evaluated. Harvest rate is estimated by equation (1) where F = 60% yr^{-1}, M = adult natural mortality (45% yr^{-1}), and t=mean period for which adults are vulnerable to exploitation (1 yr) (Gulland 1983). Harvest rate parameter estimates are from CBSAC stock assessment (CBSAC 2001) and other demographic studies (Ju et al. 1999). Harvest Recapture Rate represents the probability of harvesting a released crab and is the product of Post-release Survival and Harvest Rate. A depressed Chesapeake Bay Landings level is stipulated at 100 million individuals. During the period 1970-1999, mean landed number of Chesapeake Bay blue crabs was 190± 40 (s.d.) million.

Post-release Survival C_4 - Recruitment to Fishery			**Harvest Rate**	**Harvest Recapture Rate**	**"Depressed" Ches. Bay Landings (no.)**	**C_4 Release no. for 10% Supplement**
Size-dependent mortality	30 d	0.45%	47%	0.21%	100,000,000	4.8×10^9
model (Miller 2001):	40 d	1.0%	47%	0.47%	100,000,000	2.1×10^9
30-60 d C_1-C_4 period	60 d	5.0%	47%	2.35%	100,000,000	4.3×10^8
Hamana Lake harvest recapture rate (Okamoto 2001)				1%	100,000,000	1.0×10^9
Okayama Prefectural harvest recapture rate (Kurakawa 2001)				6%	100,000,000	1.7×10^8

tainty attendant in demonstrating stock enhancement. Fishery enhancement (put-grow-and-take) can in large part be evaluated by identifying released individuals as they are captured in a fishery (Okamoto unpubl; see Measurement of Hatchery Contribution, p. 17). Stock enhancement requires that (1) the reproductive stock has been supplemented; (2) the offspring of released individuals effectively supplement the next generation of crabs; (3) that the addition of individuals to the reproductive stock and subsequent generations are in fact supplementing the wild population rather than replacing it; and (4) negative genetic and ecological interactions between released and wild individuals are minimal. The last two issues have created much controversy for Pacific salmon, stemming from uncertainty inherent in trying to evaluate stock enhancement by comparing release and harvest numbers over generations (Hilborn and Eggers 2000). As we have discussed above for the Japanese case studies, one cannot disentangle hatchery supplementation from changes in habitat productivity, ecological and genetic interactions, and changes in exploitation patterns without substantial ancillary information.

To establish stock enhancement, one would need to follow the genealogy of released crabs and conduct broad based ecosystem-level studies on the interactions between hatchery and wild crabs and the capacity of the current ecosystem to support additional crabs (e.g., habitat productivity and predator-prey interactions). Thus, enhancement must be investigated on a system-wide basis. Given the complexity and uncertainty in establishing stock enhancement, it is no wonder that comprehensive programs of scientific evaluation are rare. Indeed, the costs of demonstrating stock enhancement of blue crabs in the Chesapeake Bay would be prohibitive, beyond the scope of any of the current programs that monitor living resources in Chesapeake Bay.

There are typically two issues that hatchery enhancement proposes to redress: (1) too few fish (i.e., overfishing, climatic productivity cycles), or (2) too little habitat. In either case, one should be careful to evaluate the extent of either problem and determine whether hatchery enhancement is an efficacious approach. In the case of blue crabs in the Chesapeake Bay, if overfishing is driving lower abundances and catches, then it would seem that addressing the source of the problem by reducing fishing would be most efficacious. If habitat is the problem, then hatcheries could hypothetically serve to bypass critical habitats, but here again we are not addressing the problem with a direct solution (i.e., habitat restoration). Rather we are proposing perpetual hatchery stocking as a surrogate for lost habitat (Lichatowich 1999). Thus, hatchery enhancement as a solution engenders considerable complexity and uncertainty because it is an indirect intervention, one that does not directly address root causes.

While there can be no imperative for hatchery enhancement of Chesapeake Bay blue crabs, there is a second more reasonable question — is there a role for artificial propagation of *C. sapidus*? The answer, informed by our Japanese experience, is a resounding yes. In Japan, the releases of tagged *P. trituberculatus* crabs have provided valuable information on growth and mortality rates, habitat requirements, migration patterns and local abundance of crabs that would not have otherwise been attainable. Propagation techniques are well developed for *P. trituberculatus* and are seeing rapid development for Chesapeake Bay blue crabs (A. Place pers. comm.). Thus, it would be quite feasible to use released crabs as environmental probes by releasing different stage crabs into varying habitats and conditions in the Chesapeake Bay (e.g. Secor and Houde 1995; Secor et al. 2000b). Such experimental releases of blue crabs could test hypotheses related to the importance of the littoral zone and submerged aquatic vegetation as nursery habitat. Released crabs could provide improved estimates of vital rates and test the efficiency of fishing and sampling gears and thereby support better stock assessments and fishery regulations. Much remains unknown about the reproductive biology and early life history of blue crabs that could become understood through experimental rearing and related laboratory-based studies. Vital attributes such as fecundity, spawning behavior and frequency, growth rate, molt increment, longevity, and juvenile energetic requirements and behaviors are better known in *P. trituberculatus* than in *C. sapidus*, due in part to artificial propagation (Ariyama 2000; Hamasaki 2000).

It is not surprising that the triumvirate of impacts to fisheries — loss of habitat, climate, and exploitation — prevail in Japan just as they do in the Chesapeake Bay. Of particular concern in Japan is the loss of shoreline habitat due to continued seawall construction and shoreline modifications. This was especially apparent in Osaka Bay (Figure 15), where scores of kilometers of sandy littoral beach habitat, considered critical nursery habitat for *P. trituberculatus*, have been converted to rocky inter-tidal environments and seawalls to curtail shoreline erosion adjacent to urban and industrial centers. It seems unlikely that hatchery releases of *P. trituberculatus* will keep pace with rates of nursery habitat loss and high exploitation: an important lesson for the Chesapeake Bay?

▸ Lessons from Japanese Hatchery-based Stocking of Portunid Crabs

A.H. Hines and A.R. Place

The Japanese hatchery-based stocking program for portunid crabs has devoted a great deal of effort to development of juvenile production, while proportionately very little effort has been allocated to evaluating the effectiveness of releasing those juveniles for stock enhancement. Comparison of the limited studies of enhancement effects in the subsystems described here provide useful insights into the effect of system scale. They also indicate the difficulties of working with a species that has a complex life cycle and that is difficult to tag. Since the studies of enhancement effects are certainly not definitive, extensive, long-term, or even conducted with the same methods, their use is more relevant for guiding additional research than for proscribing success or failure of stock enhancement in other systems. In addition, the Japanese process of hatchery releases is designed primarily for direct support of the fishery catch, and not for enhancing the spawning stock. Still, we should cautiously consider the major lessons. Clearly, there is obvious need to have research assessing enhancement activities with just as much effort and funding for assessing effectiveness as for production. Just as clearly, there is enormous need of good laboratory experimental systems for basic research and fishery management of the *Callinectes sapidus* population that has been so productive historically and is in such sharp decline currently. This research needs to be coupled with immediate and sustained improved fishery management and habitat restoration.

While the Seto Inland Sea does not appear to be as productive for *Portunus trituberculatus* as Chesapeake Bay is for *Callinectes sapidus*, the Japanese system has a much different bathymetry and lacks the extensive shallow water nurseries that characterize Chesapeake Bay. Most other estuarine systems of the U.S. that have *C. sapidus* fisheries also lack the historical productivity of Chesapeake Bay. Adjoining Delaware Bay produces about 15% of Chesapeake Bay landings and the sound system of North Carolina currently produces about 80% of the Chesapeake (as the catch in the Bay has declined to new lows and that in North Carolina has increased). The reasons for the high Chesapeake productivity or the limits to production for the other systems are not understood. Perhaps the question should not be why doesn't stocking cause the Japanese system to produce like Chesapeake Bay, but rather is the stocking system adequate to sustain or enhance fishery production in Japan, and what factors limit fishery production more generally?

While their stock enhancement effects are poorly assessed, Japanese hatchery techniques demonstrate that several species of portunid crabs can be reared in large cultures to early juvenile instars, giving credibility to the idea that this can be done with *Callinectes sapidus*. The Japanese array of hatcheries has successfully concentrated on *Portunus trituberculatus* as one of its focal species for massive production of juveniles. However, these hatcheries depend on a diverse array of multiple species that are raised sequentially over a staggered series of reproductive seasons to sustain year-round activity. They do not specialize in only one species. The rearing methods of various hatcheries all had obvious similarities, but also differed significantly in their methods of production and use of larval/juvenile food — a major component of the rearing process. They also differed substantially in their methods for "secondary rearing" of the C_1 to C_4 instars. Hatcheries also all seemed to have a significant problem in transferring early crab instars between systems (hatchery to secondary rearing, secondary rearing to release site). Hatchery collection methods of concentrating juvenile crabs in Japan are harsh (millions of early instar juveniles in tanks on the order of 200 m^3 are concentrated into 1 m^3 transport vessels) and produce high rates of damage and limb autonomy that may reduce growth rates and survival of released crabs. Improving techniques for this step could improve production and post-release survival.

Both *P. trituberculatus* and *C. sapidus* have complex life cycles in which their larvae are exported away from the adult population and into the offshore plankton where genetic stocks of adjoining subsystems are mixed. After settlement, juveniles above a critical size become benthic and remain within subsystems. Japanese research showed that it is important to grow crabs to release at a size when they are benthic and not very mobile, so that they are less vulnerable to predators than the earliest stages that are planktonic or frequently swim into the water column. For *P. triberculatus*, this is C_4-C_5 at about 20 mm CW. This size coincides with 20 mm CW *C. sapidus* that leave the SAV beds of the lower bay and settle into the subestuaries to feed and grow to maturity (Hines et al. 1987, Pile et al. 1996, Moksnes et al. 1997), except that it takes about C_7 to C_9 to attain this size in *C.sapidus* (Pile et al. 1996, Moksnes et al. 1997). Once in the subestuaries, juvenile *C. sapidus* seem to stay within the systems and grow to maturity (Hines et al. 1987, Hines et al. 1995). The major source of mortality for the juvenile *C. sapidus* in the upper bay subestuaries like Rhode River seems to be cannibalism by large crabs (Hines and Ruiz 1995), and with the reduced levels of the population of adults, juveniles currently suffer very little mortality (based on 12+ years of tethering studies). So release of 20 mm juveniles in these systems might enjoy substantially higher survival than *P. trituberculatus* juveniles in Japan, thus possibly reducing the levels of juvenile stocking needed to have an equivalent effect. Further, initial results of recent experiments in the North Carolina Sounds indicate that stocking of C_1-C_2 juveniles was successful at significantly increasing abundances in small embayments for at least several weeks (D. Eggleston, North Carolina State University, pers. comm.)

After growing to maturity and mating in the subsystems, both crab species then become mobile again and move to utilize other habits for egg production and release of dispersive larvae. Upon attaining maturity, *P. trituberculatus* migrates off shore, in an analogous fashion to *C. sapidus* migrating to the mouths of estuaries. The scale/distance of the migration depends on the system for both species. *C. sapidus* completes its life cycle by migrating 200+ km distances from the upper portion of big Chesapeake Bay but over much shorter distances throughout the rest of Chesapeake Bay and in other estuaries. The ovigerous females of both species can be found within portions of the juvenile habitat, as well as moving into separate habitat that favors release and survival of larvae. The life cycles are thus similar in that they have motile larval and early post-settlement stages and motile adult stages, while the juvenile instars remain fairly sedentary within subsystems where they grow to maturity and mate. While *P. trituberculatus* is a coastal species, *C. sapidus* utilizes estuaries for its benthic life stages.

A stocking program in Chesapeake Bay would/should short-circuit the dispersal and high mortality stages of larval development and early post settlement to release 20 mm CW crabs that remain within subestuarine systems until they grow to maturity. Once reaching maturity and mating, the large *C. sapidus* encounter the intense pot fishery as they become much more mobile and move out of the subestuaries. To promote transfer to the spawning stock, the spatial and temporal aspects of the pot fishery would have to be managed to allow corridors of migratory movement to the spawning grounds. Otherwise, it would become a put-and-take fishery.

The scale of the system and purpose of the stocking program is important. While incredible numbers (say 100 million or more) of juvenile *Callinectes sapidus* might be needed to enhance the entire Chesapeake Bay fishery, smaller estuaries or Chesapeake subestuaries might be enhanced with many fewer crabs. At the lower extreme of scale, for example, in the small Rhode River subestuary (a 585 ha embayment of the upper western shore), fishery-independent trawling and observations of fishing effort can estimate that the standing stock of fishery-legal crabs is now only ca. 2.2×10^3 crabs, and the fishery catch or production might be about 7.6×10^4 crabs. Assuming only a 10% survival of 20 mm sized crabs, it would require releasing about 7.6×10^5 juvenile crabs to double this fishery production in the Rhode River. If natural mortality of juveniles is lower (as our on-going tethering experiments indicate), then the augmentation effects would obviously increase production above this level. These considerations point to the value of testing hypotheses at varying smaller scales and at key life history stages with controlled experiments, and not attempting the obviously foolish effort to impact the entire Chesapeake Bay at once from the outset.

If the purpose of stocking is to enhance spawning stock, then additional considerations enter in. For *Callinectes sapidus* in Chesapeake Bay, there has been a concurrent, persistent and substantial reduction in the spawning stock, recruitment, and female size (Lipcius and Stockausen 2002). During recent years, the stock has become recruitment limited, apparently as a result of reduced size of the spawning stock. The baywide dredge survey indicates that the total spawning stock has declined sharply from a high of about 190 million females in 1990-1991 to a low of 42 million in 1998-1999 (Seitz et al. 2001); the past two years have declined markedly further to a level of approximately 25 million. One way to increase the spawning stock is to protect the mature and ovigerous females from fishing, either through sanctuaries or protected areas where females aggregate, or through regulating against fishing for females. Both approaches are being implemented in Chesapeake Bay to varying degrees, but these have had limited success thus far. The number of females protected in the lower Bay sanctuary is estimated to be about 8 million when the stock has been low (Seitz et al. 2001). Another way of increasing the stock might be through stock enhancement. Thus, to increase this low level of stock by 10% would require an enhancement of 800,000 females in the spawning sanctuary. Assuming that, say, 10% survival of 20 mm juveniles are released in a subsystem linked by a corridor to the sanctuary, then some 8 million juvenile females or 16 million juveniles of both sexes would be needed. The Tamano Station hatchery in Okayama, Japan produces about 10 million C_1 juvenile *Portunus trituberculatus* per year, thus indicating that such a level of production is feasible.

In addition to the stock enhancement issues of hatchery-based systems, other considerations are indicated for hatcheries. In spite of the current relatively low market price for wild crabs that precludes profitable culturing of hard crabs, we believe that some profitable niches do exist for culturing crabs. One example is the out-of-season production of soft shell crabs, which may be priced 5-7 times higher than hard crabs. To further explore this avenue the Center of Marine Biotechnology (University of Maryland Biotechnology Institute) has purchased a system from Green Solution Ltd. (Kfar Hess, Israel). This system consists of a large (20,000 L) closed recirculating tank containing two drum arrays embedded with up to 2,400 small chambers. The arrays are slowly rotated and the crab in each chamber is fed automatically when its chamber reaches the surface. Preliminary growth studies have indicated that market size for soft crabs can be attained in 2 months. This system is highly intensive (can maintain up 50 kg crabs/m^3) and has been successfully tested with other decapods such as crayfish and lobsters.

Conclusions

The current effort to assess the Japanese swimming crab industry and its relevance to the blue crab fishery in Chesapeake Bay was conducted within the context of a public debate that included many sectors of Maryland's research community, managers and the general public. The goal of this assessment was to bring back sufficient information to inform this debate and provide a better grounding for determining the feasibility of enhancing *Callinectes sapidus* populations by controlled releases of juvenile crabs. In many respects this debate mirrors those that have been taking place in a number of fisheries over many years. How one views a harvested species is of central importance and lies at the root of many of the controversies that have emerged nationwide. In a very simple sense, one might view a natural population as:

a. a stock that should be managed for harvest in a sustainable fashion,
b. an ecological unit, integral to ecosystem function on local to regional levels, or
c. a crop to be "cultivated" for beneficial uses, relative to either a or b.

These views tend not only to structure discourse but also prioritize research and management strategies. The conflicts between "fisheries management" and "stock enhancement" approaches have been well described for numerous species. The fact that in a number of cases, management strategies employing any one of these paradigms have not appeared to benefit a particular resource has proven particularly polarizing. The reality is that for Chesapeake Bay blue crabs, distinct aspects of all three of these overarching, albeit seemingly disparate views, are relevant. While the sense that *Callinectes sapidus* is both a stock and ecological unit is apparent, the widespread peeler industry is a reasonable example of how controlled "cultivation" is also at play in the region.

The intensive, long-term effort to cultivate and release Portunid crabs implemented in Japan provides important benchmarks — both in terms of the actual accomplishments and in terms of research and assessment technologies developed in Japan. The interpretation of these benchmarks cannot easily be separated from the lenses through which they are observed. The expression of these different perspectives in this report — leading to both consensus as well as disagreement — should be seen as a useful representation of these perspectives and finally as a strength of the overall effort.

There was strong consensus that information gleaned from the trip to Japan must be considered first within the context of the ongoing effort to develop new fisheries management regulations. Attaining a more stable and sustainable blue crab stock will depend upon proactive management activities like those underway through the Bi-State Blue Crab Advisory Committee and other relevant scientific/management efforts. The impacts of any propagation effort — whether for enhancement or research purposes — will likely prove significant only over the long term. With this context in mind, multiple points of agreement emerged regarding what was observed in Japan and its potential relevance to Chesapeake Bay. Such efforts are now underway through BBCAC and other relevant scientific/management entities. The impacts of any propagation effort — whether for enhancement or research purposes — will likely prove significant only over the long term and a continuing emphasis on efforts to manage the fishery in Maryland and Virginia remains a priority. With this context in mind, multiple points of agreement emerged regarding what was observed in Japan and its potential relevance to Chesapeake Bay.

The Japanese Experience

It seems clear that fishing pressure, habitat degradation and possibly climatic shifts lie at the heart of the long-standing decline of the Portunid crab fishery in Japan. The close relationship between the fishing industry and Japanese government (at the national, prefectural, and fishing cooperative level) has fostered a 30-year collaboration leading to the development of exceptional cultivation technologies. These efforts are well integrated at the societal and fisheries levels in the coastal regions where they are employed. The close linkage between the fishing cooperatives and hatchery enhancement systems has been and remains a critical element in the overall implementation of the Japanese crab enhancement effort. Indeed, cultivation of Portunid crabs is but one part of a far more extensive program to artificially rear and release juveniles of a wide range of economically important species. This approach provides an important context within which the Japanese enhancement effort should be interpreted.

Based on examinations of available data and discussions with Japanese scientists, evidence exists that the net result of enhancement efforts are most apparent in small-scale systems. In these cases, controlled releases may be sustaining harvest levels in depressed fisheries, although evidence for improved fisheries is lacking. There is no clear evidence for enhancement of the fishery in the larger system studied by the research team and a measurable impact upon natural Portunid populations (stock enhancement) has not yet been demonstrated to date in Japan. Yet the carrying capacity of the larger systems is unknown and has probably declined due to habitat degradation at the same time as the hatchery release efforts.

While advances in cultivation technology for *P. trituberculatus* have been truly remarkable, similar progress in the development and implementation of appropriate tools to assess impacts of enhancement efforts is — despite the 30-year history — lacking. Such efforts are now underway in Japan — facilitated by many of the same technological advances that have led to a detailed understanding of Portunid biology and reproduction and that have served as the foundation for cultivation efforts there.

Implications for Chesapeake Bay

The results of the fact-finding mission to Japan strongly suggest that a broad, Bay-wide effort to enhance the Chesapeake Bay blue crab fishery through hatchery efforts would face significant barriers to success. While the team diverged in their opinion about whether enhancement might be possible in a more limited context, they agreed that there were compelling reasons to develop a local capability to rear significant numbers of blue crabs. Hence there was strong concurrence that state of the art rearing facilities, capable of producing on the order of 100,000 to 1,000,000 juvenile (releasable) crabs per year would be an important (if not essential) contribution to gaining new insights into blue crab biology, while also improving our technological capabilities. They agreed that such facilities would provide tangible opportunities to advance our understanding of the reproduction, life cycle and ecology of this species. These insights and technological advances were seen as essential steps to the development of better tools for the management of the natural fishery. In addition, development of technologies directed towards economical, controlled production of very high value, soft-shell crabs was seen as an immediate benefit of such an investment in a hatchery. Key to overall success of these efforts will be a conscious attempt to integrate approaches that cross traditional boundaries and scientific disciplines — from the molecular to ecosystem scales.

While the results of the decades-long Japanese cultivation efforts were apparent, contributions made with regard to enhancement of swimming crab populations have remained clouded by an apparent lack of systematic assessment of impacts. With respect to the Chesapeake Bay blue crab, the team concurred that any and all efforts must be grounded in testable hypotheses and integrated assessment programs that include cost-benefit analyses. The team clearly diverged on the implications of scale, the importance of localized blue crab populations and the significance of temporal and spatial dispersal patterns. Thus the feasibility of enhancement emerged in very different contexts, depending upon the assumptions made and the intended outcomes for such efforts. According to one view, hatchery technology could be aimed at enhancing reproductive stocks in location-specific refuges. The other view holds that based upon the life cycle of Chesapeake Bay blue crabs, there is no practical means to enhance reproduction through localized releases. Enhancement of the stock is most efficiently accomplished through fisheries and habitat management. The divergence of opinion expressed in this regard suggests that experiments to assess scaling issues are key, and that they should be designed in a manner that leads not only to new information but to new tools.

Of the many questions that were posed during this effort, a central one was whether or not Chesapeake Bay is fundamentally different from the sites in Japan. Actually, there are a number of important similarities between the ecosystems. In both cases, there have been significant declines in natural fisheries concurrent with substantial degradation of habitat. Crab fisheries in both cases are complex and prone to high variability. Complications imposed by these factors present true challenges in the context of enhancement issues, as well as to more traditional fisheries management strategies. Of particular note, however, are the societal and management contexts in both cases. Management and engineering of coastal ecosystems and their associated fisheries are clearly more pervasive in Japan than in Chesapeake Bay. Aquaculture of many different species in Japan is extremely well integrated as is targeted stocking conducted with close coordination of producers and fishers. The model applied in Chesapeake Bay is quite different. Efforts like those of the Bi-State Blue Crab Advisory Committee suggest that the near-term approach must be grounded in consensus building and clear guidance from the scientific community. As we learn more about the suite of issues that regulate natural populations in Chesapeake Bay and as we develop a better understanding of the fundamental properties of *Callinectes sapidus*, very likely a greater set of options for maintaining a sustainable fishery will become apparent. Learning from examples like those studied in Japan will unquestionably prove an essential step in that direction.

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