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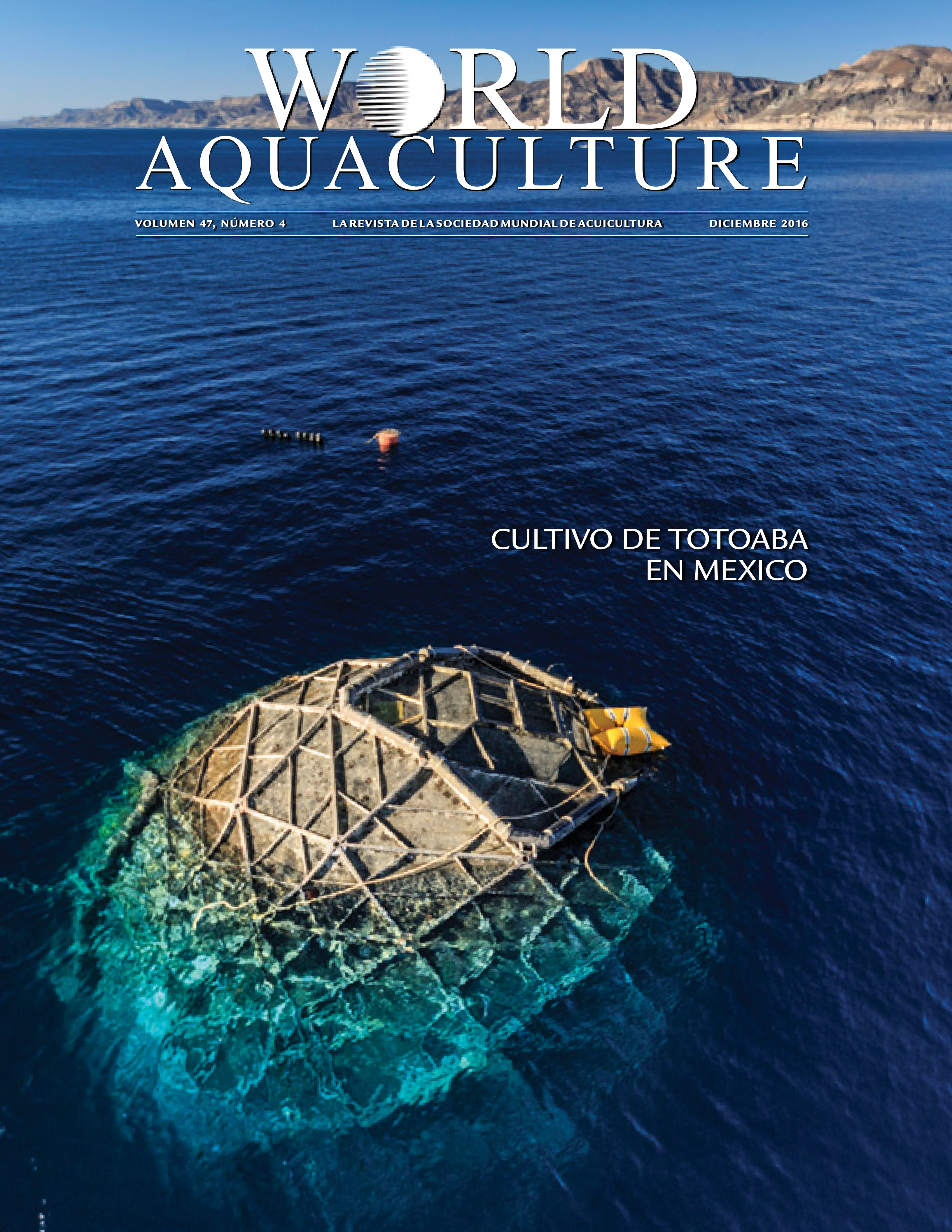
CULTIVO DE TOTOABA EN MEXICO



Totoaba Aquaculture and Conservation: Hope for an Endangered Fish from Mexico's Sea of Cortez

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This is the story of the totoaba *Totoaba macdonaldi*, an iconic and highly valuable fish from the Sea of Cortez (also known as the Gulf of California) in Mexico. Overfished to commercial depletion in the first half of the twentieth century, the species is currently listed as critically endangered and it continues to be threatened by illegal fishing, habitat degradation, and insufficient enforcement of fishing and environmental regulations. Few fish are as interesting as the totoaba from the standpoints of biology, conservation, sociology, and regulation. Now aquaculture has the potential to bring totoaba back as a sustainable resource and to generate prosperity in an economically-depressed region of Mexico.

FIGURE 1. *Adult totoaba in a broodstock maturation tank at the Earth Ocean Farms hatchery. EOF photo by Fernando Cavalin.*

FIGURE 2. *Map of Northwest Mexico showing the Gulf of California and sites relevant to the totoaba fishery (mapmaker. nationalgeographic.org, with permission).*

Totoaba are remarkably well-suited for aquaculture. Hatchery and grow-out technologies have been developed and commercial production trials are currently underway. Totoaba growth is among the fastest reported for any farmed marine fish and their quality as a food fish is high. Their status as a critically-endangered species presents unique challenges. In this article we present the history of the fishery and how perverse economic incentives and enforcement challenges resulted in its commercial depletion. We go on to present current advances in hatchery and grow-out and to show how regulatory considerations affect the species, leading to an opportunity for fishermen, regulators, researchers, aquaculturists, and conservationists to work together to restore the fishery, promote regional socio-economic development, and ensure the preservation of this iconic species for future generations.

The totoaba (Fig. 1) is the largest of the Sciaenidae, a family that includes fish commonly known as drums, croakers, corvinas, and sea bass. Totoaba can reach a weight of 135 kg, a length of 2 m, and live up to 30 years (Berdegue 1955). Their body is elongated with a sharp snout, large oblique mouth, and a projecting lower jaw. Juveniles eat mainly small crustaceans off the bottom and smaller fish from the water column. Totoaba are schooling fish endemic to the Sea of Cortez in Mexico (NOAA 2016). Adults are one of the top predator fishes in the upper Sea of Cortez and have pelagic feeding habits, favoring sardines and anchovies, although benthic crustaceans, such as shrimps and crabs are also part of their diet (Cisneros-Mata *et al*. 1995).

Totoaba spawn during the late spring in the turbid waters of the Colorado River delta, a biosphere reserve at the northernmost tip of the Sea (Fig. 2). Juveniles typically stay in that area for one or two years before migrating south on the peninsular side, following the schools of sardines and anchovies on which they feed. Their summer feeding grounds extend south to Bahia Concepcion on the Baja Peninsula, and occasionally farther south to the Bay of La Paz (Valenzuela-Quiñonez 2014), and possibly even as far as San Jose del Cabo (Peet 2009). However, we recently received a trustworthy record and photographs of an approximately 45-kg totoaba captured south of Puerto Vallarta, much farther to the south of the reported range of the species.

Fish in these summer feeding areas are thought to cross the Sea to the mainland side, south to the delta of the Fuerte River in Sinaloa, where they feed during the fall. Once they become adults after another 4 or 5 years, schools of totoaba migrate northward in the winter along the eastern coast of the Sea of Cortez, returning

FIGURE 3. *Totoaba on the beach after having their swim bladders extracted by indigenous Seri women and children in Bahia Kino, circa 1935. The boy on the left is holding a large swim bladder. Reprinted with permission from the University of Arizona Libraries Special Collections, Laurence Huey Collection # 9232.*

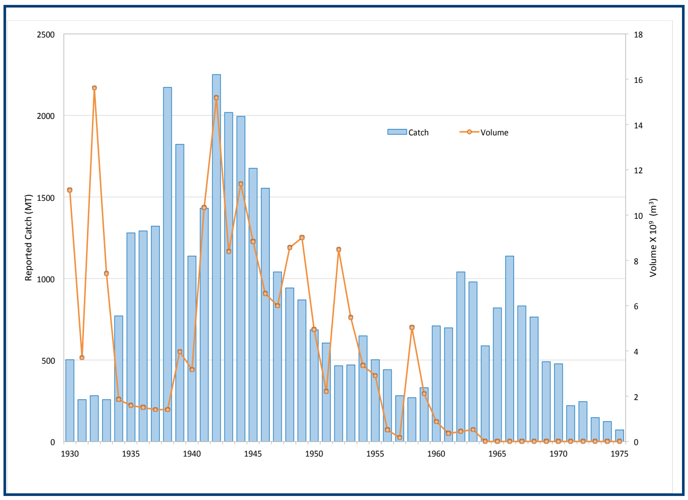

FIGURE 4. *Reported annual catch of totoaba in the Sea of Cortez, 1930 to 1975, and annual volume of Colorado River water delivered to Mexico (from Cisneros-Mata* et al. *1995).*

to their natal spawning and nursery areas near the Colorado River delta, where they remain through the spawning period the following spring (Cisneros-Mata *et al.* 1995).

The Totoaba Swim Bladder

The swim bladder is an internal, gas-filled organ that fish use to regulate buoyancy. In totoaba and other sound-producing fish it also functions as a resonating chamber for a group of specialized muscles that vibrate against it, producing a croaking or drumming sound used for communication and location purposes. The swim bladder has properties that make it highly appreciated as an ingredient in Chinese cuisine and medicine. Fish swim bladders, known as maws, are prepared in traditional soups or stews. Dried swim bladders of totoaba are known in China as *jin quian min,* which translates to "money maw." They are highly appreciated due to their similarity to those of the Chinese bahaba, or giant yellow croaker *Bahaba taipingensis,* once abundant in the south of China, but now overfished and affected by pollution to the point that it is extremely rare to catch this fish.

Totoaba maws are valued for their high collagen content and some people believe they can boost fertility, circulation, skin vitality, and longevity. Because of these perceived properties and their scarcity and illegal status, dried swim bladders of totoaba command astronomical prices. Typical prices to the consumer in Hong Kong vary from about US$2,600 for a 100-g dry totoaba bladder to US$25,000 for a 500-g unit. The Chinese have been known to stockpile the more valuable bladders as a form of speculative investment and to use them as currency.

Illegal fishermen in the upper Sea of Cortez are paid US$3,000-5,000/kg of fresh swim bladder, known as *buche de totoaba* in Mexico. Historically Chinese demand for totoaba maws drove the development of the commercial fishery in the upper Sea of Cortez and, paired with challenges in enforcement of fishing regulations, contributed to its eventual collapse in the mid-twentieth century. To this day, the economic incentives for illegal fishing and trafficking of totoaba continue to threaten the possibility of establishing a sustainable fishery and the very existence of totoaba and related valuable species.

The Totoaba Fishery

The story of the totoaba fishery is one of greed, short sightedness, and ineffective governance, tragically driving a valuable natural resource to near extinction, while contributing to the impoverishment of the local population, rather than to their prosperity. Before the commercial fishery began at the turn of the twentieth century, totoaba were part of the diet and folklore of the indigenous people. The Seri people of Sonora used harpoons with large points to spear totoaba in shallow nearshore waters (Bahre *et al*. 2000). Stories abound of how incredibly plentiful and large the totoaba were in those days.

Asian demand for swim bladders prompted the beginning of a hook and line fishery around 1910 in the coastal waters between Guaymas and the delta of the Fuerte River. Devoid of effective regulation, in a frontier region often forgotten by authorities, the exploitation of totoaba was characterized by wanton waste. Fish were dragged onto the beach, slit open, and their swim bladders were removed, dried, and shipped to China via San Francisco (Bahre *et al.* 2000). Lack of refrigeration and transport infrastructure, together with the high price of the swim bladder, made perverse economic sense for the totoaba carcasses to be left on the beaches to rot (Fig. 3). These practices accelerated so swiftly that totoaba was already commercially depleted in that zone by the 1920s, and fishing moved north towards the mouth of the Colorado River, the spawning and nursery grounds of the fish (Kira 2005).

In the early 1920s fishermen discovered that totoaba aggregated for spawning in great numbers in the waters of the Colorado River delta. The commercial fishery took advantage of this reproductive migration and thus became the most important economic activity in the area; so important that it brought about some of the first permanent settlements along the northern coastline of Sonora and Baja California (Bahre *et al.* 2000), including the fishing camps of San Felipe (1923), Golfo de Santa Clara (1927), and Puerto Peñasco (1928). A market for

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totoaba meat began to develop across the US border in California and Arizona. During those years the totoaba fishery attracted people to areas that previously had been practically unpopulated, with important sociological and ethnographic consequences. For example, permanent settlement of the Seri indigenous group in Bahia Kino ended their traditional seminomadic ways as hunter-gatherers and was the main cause of their assimilation into Mexican culture (Bahre *et al.* 2000).

Official protections

Totoaba are, on paper, one of the best protected fish on earth, but because of ineffective enforcement, these protections have failed to prevent the decline of the population:

1940: Mexico institutes a closed season for the totoaba fishery during the peak reproductive season.

1975: The Mexican government institutes a permanent ban on totoaba fishing.

1976: Totoaba is listed in Appendix I of the Convention on International Trade in Endangered Species (CITES), which restricts trade of listed species in all but exceptional circumstances. However, if a breeding facility of an endangered species in Appendix I is registered with CITES, products are treated as if they were in Appendix II, which can be traded legally.

1979: Totoaba is listed under the U.S. Endangered Species Act. This protection criminalizes the introduction of totoaba products, including swim bladders, into the United States.

1986: Totoaba is listed as endangered under the Red List of the International Union for Conservation of Nature and Natural Resources (IUCN). 1993: The Mexican Government decrees the Upper Gulf of California and Colorado River Delta Biosphere Reserve for the protection of multiple species of interest, including totoaba.

1994: The Mexican government prohibits all fishing in the nucleus of the Upper Gulf of California and Colorado River Delta Biosphere Reserve, a UNESCO's world heritage site, as well as the use of totoaba-specific gill-nets throughout the major distribution of the species.

1996: Totoaba is listed as critically endangered under the Red List of the International Union for Conservation of Nature and Natural Resources (IUCN).

2015: The Mexican government temporarily suspends gill-net and long-line fisheries in the northern Gulf of California in an effort to stop illegal fishing for totoaba and accidental bycatch of vaquita *Phocoena sinus,* the smallest and most endangered cetacean in the world. This measure includes compensation to fishermen for loss of income.

2016: Mexico makes permanent the ban on the use of gill-nets throughout the upper Gulf of California. Mexico and the US agree to increase cooperation and enforcement efforts to halt illegal fishing and trade of totoaba swim bladders.

The evolution of totoaba capture between 1930 and 1975 (Fig. 4) constitutes a typical example of overfishing and habitat degradation contributing to the collapse of a fishery. The emerging industry responded to the growing US market by developing transportation and refrigeration infrastructure and by improving fishing gear efficiency and boat facilities (Flanagan and Hendrickson 1976). Fishing effort and captures grew steadily. At its peak in 1942, roughly 2,400 t of totoaba were landed and nearly 1,300 t of totoaba fillets were exported to the United States (NOAA 2016). More effective gear and the sheer intensity of fishing pressure were decimating the population and making capture increasingly difficult.

Other than indiscriminate fishing, other causes contributed to the decline of totoaba. In the United States, completion of Hoover Dam in 1935 and Glen Canyon Dam in 1966 greatly reduced the volume of freshwater flow from the Colorado River to the Sea of Cortez (Fig. 4). With the addition of more dams along the river, little fresh water has flowed into the Sea since the late 1960s (NOAA 2016). Given the state of the Colorado River delta today, it is difficult to imagine that only 80 years ago the river delivered an average of 18 billion m^3 of fresh water per year, creating tidal estuarine conditions that extended 40 km into the upper Sea of Cortez. The delta ecosystem covered an area of 8,600 km^2 of river channels, marshes, lagoons, and riverside forest vegetation, supporting an abundance of wildlife such as jaguar, deer, beaver, migrating birds, shrimp, and fish, including totoaba (Alles 2012). Today practically all Colorado River water is diverted on both sides of the US-Mexico border to irrigate crops and for residential use. Along with the reduced flow, water temperature and salinity have increased in this area critical for totoaba spawning and early life. Incidental bycatch of juvenile totoaba by shrimp trawlers and the resulting degradation of nursery grounds have also been identified as factors contributing to decline of the fishery (Flanagan and Hendrickson 1976).

During the 1950s, with captures scarce, fishermen resorted to more aggressive methods. Gill nets replaced angling with hook and line in such quantities that they practically blocked the totoaba's migratory pathway. Totoaba are very susceptible to such methods because their population occupies limited, well-defined areas, and undergoes reproductive migrations along predictable routes. Also, because totoaba typically do not feed much during their pre-spawning migration to the north, they had up to this time been relatively protected from capture with hand lines, but gill nets decimated the fish before they could reach their spawning grounds. In further desperation, some fishermen resorted to fishing with dynamite. With such fishing pressure the reproductive population declined precipitously, and the catch decreased to about 300 t by 1958. It then increased temporarily during the first half of the 1960s, probably due to the introduction of highly efficient nylon monofilament nets, only to fall dramatically to 58 t by 1975. At that time, the fishery was completely closed by the authorities and a sanctuary zone was designated at the mouth of the Colorado River. No assessment of the totoaba population has been conducted since the fishery closed in 1975, but the fish appears to have had made a modest comeback. However, in the last few years the rebound was set back by reemergence of an illegal fishery that serves the Chinese black market for swim bladders and a regional market for meat, which is disguised by mislabeling the product as the closely-related white seabass *Atractoscion nobilis*, locally known as *cabicucho*.

Despite official protection (side bar 1), illegal fishing for totoaba continues. The pessimistic view is that the species will move closer to extinction, like the bahaba did in China. An alternative, more optimistic view is that there is still time to save the totoaba. However, this can only be accomplished with a comprehensive effort that includes effective enforcement of regulations, restoration of habitats, and a fisheries enhancement program to help make up for the loss of recruitment. In any case, aquaculture is essential for preservation of the species.

Totoaba Aquaculture

The development of totoaba as an aquaculture species was facilitated by the existing body of knowledge about two closely-related fish: the red drum *Sciaenops ocellatus*, probably the most studied sciaenid, grown for food in the Gulf of Mexico and elsewhere, and the white seabass *Atratoscion nobilis*, reared in California for restocking natural waters. Totoaba aquaculture owes much to the pioneering program created 20 years ago by the Government of Mexico at the Universidad Autónoma de Baja California (UABC) in Ensenada. Procedures for broodstock capture, maturation, larval rearing, and juvenile grow-out were initially developed at UABC (True *et al.* 2009, True 2012). This was followed several years ago with the addition of a second program at the Center for Reproduction of Marine Species of the State of Sonora (CREMES) in Bahia Kino. Both institutions have released thousands of juveniles into the wild as part of conservation efforts and have contributed to the emerging farming of totoaba by supplying fingerlings to startup aquaculture operations.

Between 2007 and 2010, two private companies started small-scale trials to grow totoaba fingerlings produced at UABC in ponds near Ensenada. Despite the many challenges associated with doing something for the first time and of the low winter temperatures in the area, the fish grew to an average of 1.5 kg in 16 months. The results were encouraging, but not enough to generate investment. In 2012, Pacifico Aquaculture stocked juvenile totoaba from the hatchery at UABC in surface cages in the ocean near Ensenada. The trials were moderately successful but again the low temperatures allowed only limited growth.

In 2013 a new player entered the totoaba arena. Earth Ocean Farms (EOF) stocked juvenile totoaba from UABC in cages in the Sea of Cortez near La Paz. By moving the fish from their northern spawning and nursery grounds to a southern location, more characteristic of the species' feeding and overwintering areas, EOF was able to take advantage of the growth potential of the species, renewing interest in commercial and conservation-minded aquaculture. The remainder of this section describes these experiences, with which the authors are associated.

The totoaba hatchery at EOF (Fig. 5) consists of broodstock husbandry, spawning, and larval culture sections, culminating with the production of fingerlings. Each of these steps has specific systems and protocols that must be operated with great care to achieve success. Because of their size, totoaba broodstock require large circular tanks (Fig. 6). To supply excellent water quality and to prevent potential pathogens, broodstock must be maintained in systems that provide adequate filtration and disinfection of the incoming water. This is achieved with recirculating aquaculture systems that recycle more than 90 percent of the system volume daily through particle and biological filters and ultraviolet sterilizers. By utilizing recirculating technologies, less "new" water is needed, improving biosecurity and water quality. Another critical factor associated with broodstock husbandry is the use of high-quality natural and prepared feeds to supply the complex mix of nutrients required for healthy broodstock maturation and egg production.

As is the case with many fish species, the main environmental cues associated with egg production and spawning of totoaba are temperature and light. By matching the natural temperature and sunlight patterns encountered throughout their annual migrations EOF developed photothermal protocols to promote gonadal maturation and spawning in the hatchery. These procedures are continuously optimized based on egg production success, a process that can take years to refine. In the interim, hormone injections are used to induce the final stages of maturation and spawning.

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Restocking programs and genetic considerations

The long-term effects of hatchery-reared fish on the fitness of wild populations are an important concern in the design and management of stock enhancement programs. Proper management is essential to maintain genetic diversity, prevent genetic contamination, and avoid genetic drift of wild populations. Diversity maximizes the potential for adaptation and survival. Improperly done, stocking of hatchery juveniles can be harmful to wild stocks. For restocking, hatchery practices should maximize genetic diversity by assembling founder populations from locations as diverse as possible, and by partially replenishing broodstock from the wild at regular intervals.

Captive fish populations tend to loose genetic diversity due to their small size and to the large contribution of a few individuals to the next generation. Coupled with the high fecundity of marine fish, this can result in large numbers of offspring from very few parents, creating serious inbreeding depression in just a few generations. This problem can be prevented by using appropriate breeding schemes and by limiting the numbers of juveniles from the same spawn that are released into the wild.

Captive populations may also loose fitness due to intentional or unintentional domestication to the culture environment. Fish produced in hatcheries for aquaculture purposes are often selected for optimum culture characteristics, which include adaption to the culture conditions and selection for commercially desirable traits, such as fast growth, efficient feed conversion, and resistance to diseases. Hatcheries that produce juveniles for restocking programs and for commercial farming need to utilize two very distinct breeding schemes; one that maximizes the genetic diversity for restocking and one that domesticates the species for optimum performance under culture conditions.

Once broodstock spawn, fertilized eggs float to the surface and can be harvested with skimmers and concentrated into collectors. Totoaba tend to group-spawn at night, and successful spawning results in egg collectors with millions of eggs. Fertilized eggs are transferred from egg collectors to hatching tanks and eggs typically hatch after 24 hours at 23 C. After hatching, larvae are transferred to rearing tanks. Larviculture requires strict management, water filtration, and disinfection, so recirculating systems are also used. During larval stages (Fig. 7), live feeds such as rotifers and *Artemia* are cultured separately, enriched, and fed to larvae multiple times per day. *Artemia* are the final live feed, after which larvae are transitioned to commercial weaning diets. Once fully weaned, fingerlings are fed solely on fine crumbled feeds of the appropriate size for their mouth gape. Larvae remain in these tanks for 30 days, until they are fully weaned and hardy enough to be transferred to fingering tanks. In these finishing tanks, they are grown to 10-50 g individual weight as required for subsequent grow-out in sea cages or for transfer to appropriate locations for stock enhancement.

Totoaba fingerlings produced in the hatchery are transferred to marine cages for grow-out after they reach 10 g. Transfer is done carefully to avoid excessive stress from handling or from sudden changes in temperature, pH, or water depth. Spherical and submersible Aquapod® cages with volumes of 1,600, 3,600, or 4,800 m^3 are used for grow-out (Fig. 8). Initially fry are pumped into nursery nets placed inside the Aquapod® cages, where they can be monitored and fed intensively. Once they reach 250 g average weight, they are released from nursery nets to have access to the full volume of the cages. Feeding is done remotely with an automated delivery system and video monitoring. A commercial marine fish ration with 46 percent protein and 13 percent fat is fed one to three times per day. Figure 9 depicts the growth of a batch of totoaba

FIGURE 5. *The Earth Ocean Farms totoaba hatchery in La Paz, Baja California Sur, Mexico. EOF photo by Fernando Cavalin.*

FIGURE 6. *One of Earth Ocean Farm's 80-m^3 totoaba broodstock maturation tanks. Note cover to allow photoperiod manipulation, windows to observe fish behavior, and water recirculation equipment on the right. EOF photo by Lorenzo Juarez.*

The mixed blessing of high-value natural resources

High-value natural resources such as ivory, gemstones, and precious metals can be sources of economic prosperity when they are well-managed, bringing higher standards of living and facilitating regional prosperity. The inverse result is unfortunately common and well known to economists as part of the "resource curse" or the "paradox of plenty." The general differences in management and governance between these two opposite outcomes deserve consideration as applicable to cases such as the totoaba swim bladder.

In general, where high-value resources result in socio-economic degradation, it is because their exploitation is controlled by outsiders who syphon revenue out of local communities under the neglect or complicity of unaccountable and corrupt authorities. The local population is viewed mostly as a source of cheap labor. Regulations tend to be non-existent, overly complex, or applied selectively. Exploitation of these resources often results in their depletion and related environmental destruction. Products are commoditized and their origin is disguised. These so-called "conflict resources" are often coupled to social unrest, insecurity, and/or organized crime.

High-value resources have better chances of fostering prosperity when managed under cooperative partnerships between local stakeholders and accountable institutions with agendas focused on the aspirations and circumstances of local community members. In this approach the rules and regulations are fair, and not only followed, but also enforced by the users. Decision making is participatory, focused on local people, and based on their needs and objectives. A significant portion of the revenues stays in the local communities and is applied with transparency to their improvement, notably in the form of investments in people and projects that create future wealth, livelihoods or human well-being. The resource is managed with integrity and with environmental, economic, and social sustainability in mind. Products are branded and proudly identified as to their origin.

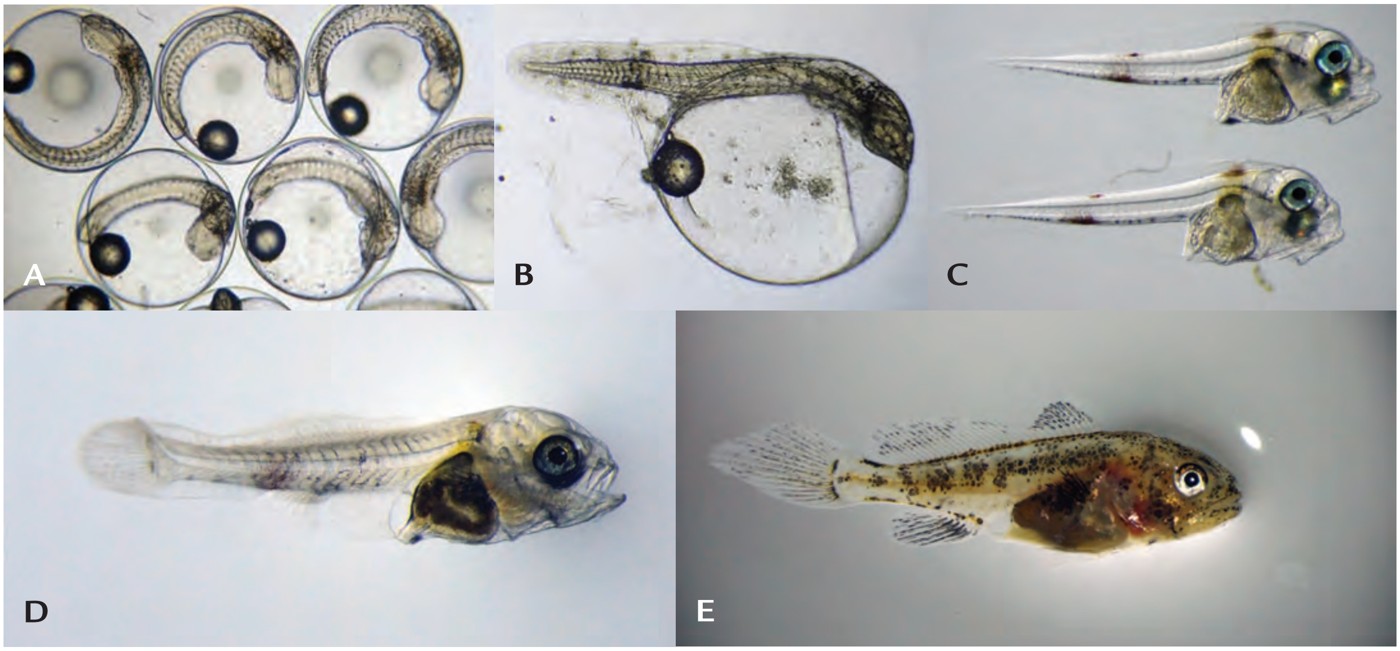

FIGURE 7. *Totoaba eggs, and larvae. (A) Eggs at embryo stage prior to hatching, 950 µm diameter. (B) Newly hatched yolk-sac larva, 2.9 mm length. (C) 5 days post-hatch larva, 4.1 mm length. (D) 13 days post-hatch larva, 5.9 mm. (E) 19 days post-hatch fry, 7.4 mm length. EOF photos by Fernando Cavalin.*

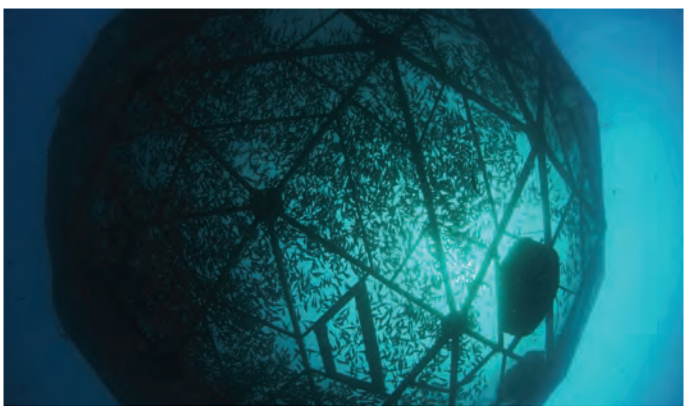

FIGURE 8. *Submersible, 1600-m*^{3} *Aquapod® cage with juvenile totoaba. Photo by Johnny Friday.*

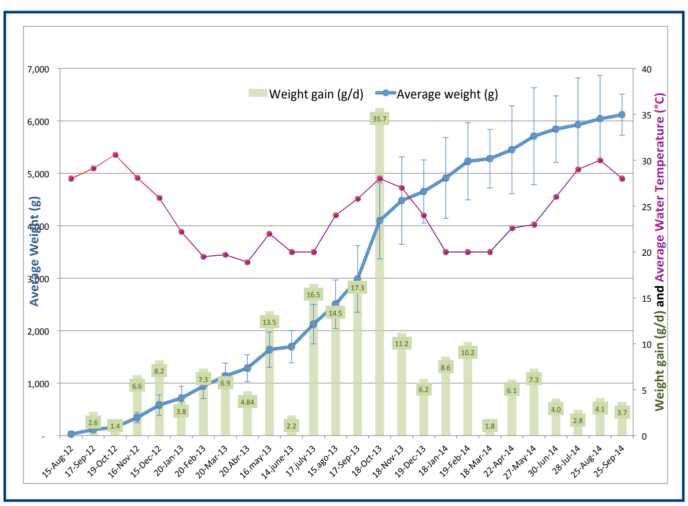

FIGURE 9. *Growth of a batch of totoaba at Earth Ocean Farms during 2012-2014. Average daily weight gain bars and surface water temperatures on the right axis.*

fingerlings from 2013 to 2015. In general, fry stocked in the summer attain an average of 2.5 kg in one year and 6 kg in two years. Feed conversion has averaged 2.5 and weight gain approximately 7.5 g/d.

EOF's pilot operation has invested significant time and resources in optimizing and automating offshore farm functions, such as controlling cage buoyancy/rotation, cleaning, feeding, monitoring, and harvesting. A comprehensive environmental monitoring program is in place to ensure water and ocean bottom sediment quality remains optimal. This totoaba farming model is very resource-efficient. Projecting data from the pilot-scale farm to a larger scale, it is theoretically possible to produce 2, 300 t — equivalent to totoaba landings at their peak in 1942 — with a 30-cage farm that occupies less than 30 ha. In practice, this would be done in a much larger area or in multiple locations to allow for buffer zones and for assimilation of waste nutrients by the ocean's natural processes.

Stock Enhancement

The totoaba fishery collapsed, like others worldwide, from overexploitation of stocks and habitat degradation. This is not an isolated phenomenon but merely another example of a global trend. Almost one-third of worldwide commercial fish stocks are now fished at biologically unsustainable levels and many also suffer from the effects of habitat degradation (FAO 2016). Viable measures to restore these fisheries include regulation of fishing effort, protection or restoration of habitats, and stock enhancement programs. Rehabilitation of the totoaba resource may require all three approaches.

When properly done, culture-based fisheries enhancement has the potential to generate many benefits. In biological terms, stock enhancement can increase the yield and productivity of fisheries, aid in conservation and restoration of endangered or overfished stocks, and mitigate the effects of habitat destruction. These can translate

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TABLE 1. Components of the responsible approach to marine stock enhancement (from Lorenzen *et al.* 2010).

STAGE I: *Initial appraisal and goal setting*

1. Understand the role of enhancement within the fishery system.
2. Engage stakeholders and develop a rigorous and accountable decision-making process.
3. Quantitatively assess contributions of enhancement to fisheries management goals.
4. Prioritize and select target species and stocks for enhancement.
5. Assess economic and social benefits and costs of enhancement.

STAGE II: *Research and technology development, including pilot studies*

6. Define enhancement system designs suitable for the fishery and management objectives.
7. Develop appropriate aquaculture systems and rearing practices.
8. Use genetic resource management to maximize effectiveness of enhancement and avoid deleterious effects on wild populations.
9. Use disease and health management.
10. Ensure that released hatchery fish can be identified.
11. Use an empirical process for defining optimal release strategies.

STAGE III: *Operational implementation and adaptive management*

12. Devise effective governance arrangements.
13. Define a fisheries management plan with clear goals, measures of success, and decision rules.
14. Assess and manage ecological impacts.
15. Use adaptive management.

into economic and social benefits, including new opportunities for fishermen and better management of common resources (Lorenzen 2008). Culture-based fisheries enhancement is a set of management approaches involving the release of cultured organisms to enhance or restore fisheries by increasing recruitment and spawning biomass (Lorenzen *et al*. 2013, Støttrup and Sparrevohn 2007). The practice began in the 1870s with hatchery releases of cod and plaice (Kitada and Kishino 2006), but these early attempts were hindered by limited understanding of the ecology and genetics of wild populations and by an emphasis on the quantity of fry released rather than on quantitative measures of success (Lorenzen *et al.* 2010, Leber 2013). This changed in the 1970s, when results of salmon restocking programs began to be published (Hager and Noble 1976).

A renewed, responsible approach to stock enhancement emerged in the 1990s, with an increased focus on quantification of effects, significant progress in fisheries ecology, effective technologies for reproducing marine species in hatcheries, and improved methods of fish tagging (Blankenship and Leber 1995, Leber *et al*. 2004, Lorenzen 2008, Lorenzen *et al.* 2010, Lorenzen *et al*. 2012, Leber 2013, Lorenzen *et al*. 2013). This approach involves more than simply releasing hatchery-reared fish into the wild. The current approach requires a thorough understanding of the ecological processes affecting the fishery, close integration with fisheries management, broad inputs from stakeholders, serious consideration of the genetic constitution of released organisms (side bar 2), and quantitative goals and measures of success. Table 1 summarizes the stages and elements of a responsible approach to marine stock enhancement (Lorenzen *et al*. 2010).

The concept has been implemented over the last two decades and there are now successful examples with salmon in Alaska (Stopha 2016), turbot in Denmark (Strøttrup *et al*. 2002), red sea bream and Japanese flounder in Japan (Kitada and Kishino 2006), white seabass in California (Gruenthal and Drawbridge 2012), and red drum in Texas (McEachron *et al*.1993), to name a few. The last two examples refer to sciaenid species related to totoaba. A restocking program for totoaba is sensible because hatchery-produced juveniles could mitigate the lack of natural recruitment due to overfishing, habitat degradation, and direct removal of juveniles by shrimp trawlers. This would be a case similar to that of the role of salmon hatcheries in replacing fish runs lost to dams and reduction of habitat along the Pacific coast of North America.

Given the current state of the totoaba resource, the fish could become extinct soon. A vigorous and comprehensive effort for totoaba restoration is necessary. Lessons can be drawn from the management of other high-value natural resources (side bar 3). Such a rebuilding effort would be difficult, but not impossible. It would require the political will to create effective institutional arrangements and multi-stakeholder agreements that include fishermen, aquaculturists, government, academics, and environmentalists. The means, scope, and goals of a comprehensive fishery management system would have to be determined, and incentives would have to be created for behaviors that contribute to positive outcomes. As a start, effective enforcement of existing regulations is essential. These should be coupled with measures to protect and restore the estuary of the Colorado River and adjacent nursery areas. Because the success of restocking programs depends on knowledge of the ecosystem and population dynamics, a proper assessment of the totoaba population should be conducted, ideally by the fisheries research arm of the Mexican government. With these efforts in place, a collaborative restocking program can be designed and implemented.

Hatchery technology for totoaba is well developed and there are currently three geographically-diverse hatcheries (UABC in

Ensenada, CREMES in Bahia Kino, and EOF in La Paz) producing juveniles from wild-caught brood stock. In the last few years, these hatcheries have released thousands of totoaba juveniles to the Sea of Cortez. The most recent release, done by EOF at Bahia Concepcion in August 2016 (White 2016), consisted of 15,000 individuals with an average weight of 15 g. Totoaba hatcheries should increase cooperation to include exchanges of germplasm and coordinated breeding plans to minimize inbreeding.

A scientific advisory board could coordinate breeding plans and release strategies such as the magnitude, location, size, season, and conditioning methods used to maximize behavioral adaptation and survival of releases to the wild. Areas and seasons for release should be investigated. The species' response to the reversion of salinity in the Colorado River delta has not been documented, but reproduction continues to occur, either at the high salinities now characteristic of the area, and/or at lower salinities present in other estuaries. An argument can be made to stock juveniles in areas such as the Fuerte River estuary, where totoaba are known to exist and could be using as a nursery, or in other similar areas.

Notable progress has been achieved using techniques from molecular biology to genotype hatchery broodstock, their progeny, and the wild population (Garcia de Leon *et al*. 2010). These techniques could help guide a restocking program by estimating consanguinity and ascertaining parentage. Finally, genetic management and restocking strategies have been developed for the white seabass enhancement program that Hubbs SeaWorld Research Institute manages in California (Gruenthal and Drawbridge 2012), which could be adapted and expanded to apply to a world-class totoaba restocking program.

The Future

Totoaba is very well-suited for aquaculture. Farming of this species can contribute to food production, socioeconomic development, and reduction of fishing pressure on the wild stock. Totoaba aquaculture has the potential to become an important aquaculture industry in the Sea of Cortez. In time, totoaba could also become a culture-enhanced fishery, much like salmon in Alaska.

Because of their endangered status, totoaba are regulated in Mexico mainly by environmental rather than fisheries authorities. Because it has evolved into an emerging aquaculture species before regulation has had a chance to catch up, totoaba aquaculture is operating under old legislation that did not anticipate farming an endangered fish and thus does not directly apply. Consequently totoaba aquaculture is constrained by regulations originally intended to apply to the management of endangered terrestrial species on game-hunting ranches. The permit to culture totoaba in an aquaculture facility applies to an environmental management unit, where an endangered species is managed for conservation and exploitation. The harvest permit is granted for a pre-determined number of animals, consistent with the sustainable yield from the unit. The permit to sell the harvest originates from the first time animals are sold from an environmental management unit (hatchery or farm) and extends through production and sales channels to the final buyer. Applying these regulations to fish farming has not been straightforward and their interpretation has been discretionary.

Regulatory certainty and consistency are needed if totoaba aquaculture is to become a source of prosperity. On the other hand, effective mechanisms are also needed to ensure that farming is not used to market illegal wild-caught totoaba, further depleting their population. Such mechanisms can include rigorous traceability, tagging and/or marking methods to distinguish wild from farmed fish, and marketing and educational programs.

Coastal settlements around the northern Sea of Cortez lag behind other areas of Mexico in development and lack basic services and infrastructure. Fishing constitutes the main means of subsistence in these communities. To have such a valuable, renewable natural resource as the totoaba in the area points to an opportunity and a moral imperative to rebuild and manage a sustainable fishery to improve the local economy. Such an opportunity should not be wasted and could be combined with developing related industries such as aquaculture, high-value sport fishing, and nature- or adventure-focused tourism.

The totoaba is a unique and emblematic fish that should be protected and utilized to its full and sustainable potential for the benefit of local communities through fisheries and aquaculture. We envision a future in which exemplary enforcement of regulations and restoration of habitats turns the current situation into a success story of stock rehabilitation and fisheries management. Aquaculture can play a part in this future by producing juveniles for restocking using current guidelines for responsible fisheries enhancement. Aquaculture has an important role in promoting conservation, sustainable development, and food security through production of juveniles for fisheries enhancement and for the production of food fish and swim bladders for national and export markets. Any such program will require regulators, environmental organizations, fishermen, private industry, academics and the local population to work together for the common good.

Notes

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