Culture of Marine Sciaenids in Low Salinity: an Opportunity for Expanded Aquaculture in Mexico

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Abstract

The Sciaenidae is a highly diversified family of fish with worldwide distribution across warm-temperate and tropical waters. Numerous sciaenids are cultured commercially in different regions of the world. Most sciaenids are marine, but many representatives are euryhaline, *i.e.*, capable of withstanding a wide range of environmental salinities. Surprisingly enough, the family encompasses 25 strict freshwater species within six genera. Evidence of the salinity tolerance of various species of sciaenids across the world is large enough to suggest that commercial culture of sciaenids in low salinity is possible. In Mexico, among finfish families subjected to fisheries in the Pacific Ocean, Sciaenidae contributes with the largest number of captured species (24 species), while 13 species of sciaenids are captured in the Gulf of Mexico and the Caribbean Sea. Besides the 37 species exploited in commercial fisheries, there are more representatives of this family in Mexico. For example, at least 30 species of sciaenids are found in the Gulf of California alone. Taking into account this richness of species, some have been evaluated as candidates for aquaculture, including totoaba (*Totoaba macdonaldi*), the Gulf corvina (*Cynoscion othonopterus*), and the shortfin corvina (*C. parvipinnis*). All three species have shown to be euryhaline. For *T. macdonaldi*, definite proof that it can be cultured to marketable size in low salinity is presented. The information herein presented provides opportunities for expanded aquaculture of sciaenids in Mexico, using a variety of water sources, such as brackish or diluted saltwater, rivers, dams, or ground waters, perhaps in locations in which commercial culture was not previously thought possible.

Keywords: Aquaculture, Sciaenids, Euryhaline, Low salinity.

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I-Introduction

Many aquatic species are not capable of tolerating changes in water salinity. These species, referred to as stenohaline (Gr. stenos: narrow + halinos: saline), are restricted to live in specific environments, for example either salt or freshwater. Conversely, some are capable of withstanding an ample range of environmental salinities, and are thus named euryhaline (Gr. eurys: wide, broad + halinos: saline). Euryhalinity is of great interest from various perspectives, including the physiological, biological, and evolutionary. Furthermore, euryhalinity may have important practical implications, for example, for the rearing of marine organisms in low-salinity environments, such as brackish or diluted saltwater, as well as river, dam, or ground waters, in which commercial culture was not previously thought possible. The Pacific white shrimp, *Litopenaeus vannamei*, and the black tiger shrimp, *Penaeus monodon*, are excellent examples that the commercial culture of marine, euryhaline organisms is possible in unorthodox, low-salinity environments. Because of their amazing capacity to grow and survive in low salinity waters, *L. vannamei* has been cultured in groundwaters in the states of Alabama, Texas, Arizona, North Carolina, and Florida in the United States, as well as in other countries, such as China, Ecuador, Brazil (Roy *et al*. 2010), and Mexico (Perez-Velazquez *et al*. 2009). In turn, significant productions of *P. monodon* have been achieved in Thailand using brine solution obtained from saltwater evaporation, which is added to freshwater ponds to adjust salinity to values typically ranging from 2 to 5 g L^{-1} (Flaherty & Vandergeest, 1998; Flaherty *et al*. 2000).

Euryhalinity also has been reported to occur in finfish, with the best documented examples represented by sciaenids. Commonly known as weakfishes, drums, and croakers, sciaenids are sport and food fish found around the world in warm-temperate and tropical waters (Chao, 1986; Sasaki, 1989). Sciaenid species from the genus *Cynoscion* spp. are sometimes named corvine/corvina (Lat. corvinus, from corvus: raven), because their lower jaw protrudes slightly beyond the upper jaw, resembling a raven's beak. During reproduction, sciaenids usually seek out estuarine areas where they encounter waters of lower salinity to spawn (Acha *et al.* 1999). For instance, it is well documented that the Gulf corvina, *Cynoscion ohtonopterus*, forms seasonal aggregations in the Colorado River Delta,

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upper Gulf of California, Mexico, where they encounter lower salinities and spawn (Rowell *et al*. 2005). In many instances, juveniles spend the first stages of their life cycle in these environments until they are ready for recruitment and migrate back to the sea. Studies of these estuarine-dependent reproductive patterns of sciaenids indicate that, depending on the species, they can tolerate environmental salinities ranging from 5 to 42 g L^{-1} (Cárdenas, 2012).

Sciaenids are cultured in different regions in the world, with an overall production of ca. 124,000 metric tonnes recorded in 2008 (FAO, 2012). The most widely cultured sciaenid species are the yellow croaker, *Pseudosciaena crocea*, the red drum, *Sciaenops ocellatus*, and the meagre, *Argyrosomus regius* (Cárdenas, 2012). Among these, *S. ocellatus* provides an excellent indication that culture of sciaenids is possible in low salinity. Although it is extensively cultured in seawater in the coasts of both the Atlantic Ocean and Gulf of Mexico in the United States, it has been documented that it may grow well in low-salinity brackish waters, as long as chloride concentrations exceed 130 mg L^{-1} (Miranda and Sonski, 1985; Matlock, 1990; Wilson, 1990). Because of their firm, mild-flavored white meat, sciaenids are highly appreciated as food fish in local and international markets.

The present manuscript describes recent advances in low-salinity culture of fish belonging to the Sciaenidae family in Mexico.

II-Biogeographical notes on the Sciaenidae

The Sciaenidae is a highly diversified family of fish with worldwide distribution across warm-temperate, tropical, and typically not cold waters. It is one of the eight largest families within the Order Perciformes (Nelson, 2006). The Sciaenidae groups together 66 genera and 291 species (Eschmeyer & Fong, 2013). Based upon the classification of the world's oceans into four major basins, Eastern Pacific, Western Atlantic, Eastern Atlantic, and Indo-West Pacific (Springer, 1982), the greatest diversity of genera and species of sciaenids is found in the Indo-West Pacific basin, with 93 species. It is followed by the Eastern Pacific and Western Atlantic basins, of equal species richness in relation to one another, each with 82 species. Finally, the Eastern Atlantic basin is the least diverse, with

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19 species (Lo *et al*. 2015). Most sciaenids are marine, although many species are known to inhabit brackish waters of estuaries and coastal lagoons. Surprisingly enough, the family encompasses 25 strict freshwater species within six genera. They are particularly important as a testament to the euryhaline nature of fish belonging to this family. The vast majority of these freshwater sciaenids, 23 species in four genera, are endemic to the Amazon basin and other parts of South America, one species is located in North America (*Aplodinotus grunniens*), and one in Southeast Asia (*Boesemania microlepis*) (Table 1) (Sasaki, 1989; Lovejoy *et al.* 2006; Lo *et al*. 2015). The evolutionary incursion of the Sciaenidae, and other freshwater fish species of marine lineages, from the marine to the freshwater environment has fascinated researchers for a long time. Ironically, the presence of strict freshwater sciaenids in different continents is not associated with a common inland freshwater ancestry prior to the breakup of Gondwana in the cretaceous period. Instead, it is believed that sciaenids invaded the freshwater habitat much more recently in three independent events in the Miocene.

Table 1. Geographical distribution of strict freshwater genera of the Sciaenidae.

Genera	Distribution	Source
	NORTH AMERICA	
Aplodinotus sp.	United States, Mexico.	Sasaki, 1989
	SOUTHEAST ASIA	
Boesemania sp.	Thailand, Vietnam, Cambodia, and Sumatra.	Kottelat *et al*. 1993
	SOUTH AMERICA	
Plagioscion sp.	From northern Venezuela to lowlands of Argentina.	Chao, 1978
Pachypops sp.	From northern Venezuela to lowlands of Argentina.	Chao, 1978
Pachyurus sp.	From northern Venezuela to lowlands of Argentina.	Chao, 1978
Petilipinnis sp.	Brazilian Amazon basin, Cuyuni and Essequibo river basins in Guyana	Casatti, 2002

The South American incursion of the lineages *Plagioscion*/Pachyurinae is believed to have occurred 21 million years ago (Ma). The Caribbean Sea is considered the most likely point of entry, with transgressions extending into the upper Amazon basin. In North America, the freshwater invasion by *Aplodinotus* is hypothesized to have occurred 19.5 Ma, and by

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Boesemania in Southeast Asia close to 10.3 Ma (Lovejoy *et al*. 2006). The idea that sciaenids must have performed a gradual marine-to-freshwater adaptation (Cooke *et al*. 2012) has been objected in favor of a recent theory of ecological fitting, *i.e.*, a common sciaenid ancestor/lineage must have already been capable of tolerating freshwater, facilitating the colonization of this environment (Boeger *et al*. 2015).

III-The Sciaenidae of Mexico: important fisheries species and candidates for aquaculture

Fisheries species of sciaenids are captured seasonally in Mexico along the coasts of the Pacific Ocean and the Gulf of Mexico. Genera exploited include *Atractoscion, Menticirrhus, Sciaenops, Micropogonias, Parolonchurus, Cynoscion, Leiostomus, Bairdiella, Larimus,* and *Cheilotrema,* to mention a few. Among finfish families exploited for fisheries in the Pacific Ocean, Sciaenidae contributes with the largest number of captured species with a total of 24 species, while 13 species of sciaenids are captured in the Gulf of Mexico and the Caribbean Sea (Fuentes-Mata and Espinoza-Pérez, 2010). In general, sciaenids are subjected to artisanal fishing and official fisheries statistics are fragmentary. The main exploited species by volume in the Pacific Ocean is the Gulf corvina, *Cynoscion othonopterus,* endemic to the Gulf of California, with a peak production of 6,000 tons in 2002, which decreased to 3,727 tons in 2010 (SAGARPA, 2012). The bigeye croaker, *Micropogonias megalops,* also endemic to the Gulf of California, is the second most important species, with 2,000 tons landed in 2015. Other sciaenids, also appreciated as game and food fishes in this region, include the shortfin corvina, *Cynoscion parvipinnis, C. nobilis, C. reticulatus, C. xanthulus, Atractoscion nobilis, Bairdiella incista, Cheilotrema saturnum, Larimus acclivis, Menticirrhus nasus, M. panamensis, M. undulatus, Roncador stearnsii, Umbrina roncador, and U. xanti* (Gobierno del Estado de Baja California, 2000-2015). In the Gulf of Mexico, fish landings of *Cynoscion arenarius, C. nebulosus*, and *C. nothus* collectively amounted to ca. 3,000 metric tonnes in 2008 (SAGARPA, 2012). Other sciaenids associated with these fisheries, but captured in smaller quantities, are *Bairdiella chrysoura, B. ronchus, Menticirrhus americanus, M. littoralis, M. saxatilis, Micropogonias undulatus, Pogonias cromis,* and *Sciaenops ocellatus*

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(SAGARPA, 2012). In addition, the geographical distribution of the only North American strict freshwater sciaenid, *Aplodinotus grunniens*, extends from the United States, including the Rio Bravo in the Atlantlic basin, to the Usumacinta-Grijalva River in southeastern Mexico (Espinosa-Perez *et al.* 1993). Highly appreciated as food fish, this species is of local economic importance in some dams, such as "Malpaso" in the state of Chiapas (Anzueto-Calvo *et al*. 2013).

The development of technology for the commercial culture of the sciaenids *P. crocea*, *S. ocellatus*, and *A. regius* in Asia, the Americas, and Europe, respectively, is *fait accompli* (Cárdenas, 2012). Taking into account the richness of species of sciaenids found in Mexico, mass culture of sciaenids may soon become a reality. Several candidate species have been identified. Without doubt, totoaba, *Totoaba macdonaldi*, is a prominent candidate species. The story of totoaba is a fascinating one. It is endemic to the Gulf of California and a true giant, the largest representative of the family Sciaenidae, reaching up to 2 m (6.5 feet) in length and 135 kg (298 lbs) in weight (Flanagan and Hendrickson, 1976). *T. macdonaldi* supported a prosperous fishery in the upper Gulf of California in the 1950s (Bobadilla *et al*. 2011). Due to overfishing, it was catalogued as an endangered species and fishing was completely banned since 1975 (Mexican Official Norm NOM-059-ECOL-1994). Reproduction of totoaba in captivity was first accomplished at Universidad Autonoma de Baja California (UABC) in Ensenada, Baja California, Mexico. Recently, a second successful breeding program was established for stock enhancement and aquaculture purposes at the Center for Reproduction of Marine Species of the State of Sonora (CREMES), Kino Bay, Sonora, Mexico. Since 2013, CREMES has released thousands of juvenile fish into the wild every year near Kino Bay, Gulf of California. Interestingly, captive rearing has shown that this species has very fast growth rates. With its highly appreciated meat quality, as well as the stratospheric prices its swim bladder fetches in specialty Chinese cuisine markets (Juarez *et al*. 2016), totoaba has been targeted for expanded aquaculture in Mexico. Currently, the private company Earth Ocean Farms conducts commercial growth trials in submersible cages near La Paz, Gulf of California. The results have been more than encouraging and have shown that totoaba can reach 2.5 kg of weight in one year and 6 kg in two years (Juárez *et al*. 2016).

Other sciaenid species, the Gulf corvina, *Cynoscion othonopterus* (Figure 1), and the

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shortfin corvina, *Cynoscion parvipinnis* (Figure 2), have also been evaluated as candidates for aquaculture at the University of Sonora and other institutions in the northwestern region of Mexico. Using fingerlings and juveniles produced at CREMES, various nutritional aspects of these species have been evaluated. Although these studies have been conducted in short-term trials, 6 to 8 weeks, and at small scale in experimental tanks, it has been possible to show that growth rate of both species, although not as spectacular as that of totoaba, compares well with the average growth rates of other sciaenids of similar size (Perez-Velazquez *et al.* 2015; González-Félix *et al*. 2015; Minjarez-Osorio *et al*. 2016; González-Félix *et al.* 2016).

Figure 1. Gulf corvina, *Cynoscion othonopterus*.

The former examples of sciaenid species as candidates for aquaculture may be just the tip of the iceberg. In Mexico, there are more representatives of the family than the species described earlier as fisheries species. For example, at least 30 species of sciaenids are found in the Gulf of California alone (Van der Heiden, 1985). The vast majority of these species have not been evaluated for aquaculture. The possibilities of advancing the culture of sciaenids in the near future in Mexico is certainly promising.

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Figure 2. Shortfin corvina, *Cynoscion parvipinnis*.

IV-Culture of sciaenids in low salinity: the evidence so far

Red drum, *S. ocellatus*, is an excellent example that euryhaline organisms can be reared successfully in low salinity. Forsberg *et al*. (1996) reported that red rum shows adequate growth rates in groundwaters at salinities between 5 and 15 g L^{-1}. It has also been reported that it may grow well in low-salinity brackish waters, as long as chloride concentrations exceed 130 mg L^{-1} (Miranda and Sonski, 1985; Matlock, 1990; Wilson, 1990). Furthermore, in a 6-week feeding trial, weight gain of red drum was greater when reared at 5 g L^{-1}, as compared to full strength seawater (Craig *et al*. 1995). As additional proof of its ample tolerance to low salinity, 1.5 to 2 million red drum fingerlings are stocked annually for sport fishing into freshwater reservoirs in Texas, USA, such as Calaveras and Victor Braunig in the vicinity of San Antonio, as well as Tradinghouse Creek near Waco, and Fairfield, named after the town that bears the same name (Hodge, 2006). Because of the good response of red drum to low salinity, growth trials with this species are routinely conducted at salinity of ca. 7 g L^{-1} at the Texas A&M Aquacultural Research and Teaching Facility of Texas A&M University, College Station, Texas, USA, which is preferred over natural seawater salinity (Rossi *et al*., 2015; Minjarez-Osorio *et al*. 2016).

In Australia, approximately 2.5 million ha of land, formerly used for agriculture, have been affected by secondary salinization of groundwaters, which has sparked interest in using them for inland aquaculture (Doupé *et al.* 2003; Partridge *et al*. 2008). The mulloway,

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Argyrosomus japonicus, has been targeted as one of the species of choice for this purpose in Australia, in view of its great potential for low-salinity inland culture (Doupé *et al.* 2003). *A. japonicus* is a sciaenid which is normally produced in sea cages (O'Sullivan *et al.* 2007), but adequate growth of this species in inland saline groundwaters was reported by Doroudi *et al*. (2006). In fact, *A. japonicus* has already been cultured commercially using saline inland water in that country (Partridge *et al*. 2008).

The yellow croaker, *Pseudosciaena crocea*, an economically important coastal species from Asia, and silver kob, *Argyrosomus inodorus*, also of economic importance in the southeastern Atlantic coast of Africa, add to the list of sciaenids known to tolerate low salinity well. Growth of these species is at least as adequate at low salinity as in natural seawater (Ferreira *et al*. 2008; Wang *et al*. 2016). For the Atlantic croaker, *Micropogonias undulatus*, growth observed in low salinity was greater than in full strength seawater (Peterson *et al*. 1999), similarly to reports for red drum (Craig *et al*. 1995).

In Mexico, the salinity tolerance of *T. macdonaldi*, *C. othonopterus*, and *C. parvipinnis*, has been investigated. All three species have been shown to be euryhaline, their isosmotic salinities were established at 12.3, 9.8, and 13.4 g L^{-1}, respectively. After 6 weeks of culture, growth rate of *C. othonopterus* was similar throughout the salinity range of 5 to 35 g L^{-1} (Perez-Velazquez *et al*. 2014). For *T. macdonaldi* and *C. parvipinnis* reared during 8 weeks, somatic growth was greatest at 10 g L^{-1} (González-Félix *et al*. 2017). Specific growth rate (SGR) observed at salinities of or above 10 g L^{-1} for these species (0.9 to 2.3% d^{-1}) compared favorably to the range of SGRs, from 0.7 to 2.5% d^{-1}, reported for a number of other sciaenids, such as *S. ocellatus*, *A. japonicus*, *Sciaena umbra*, and *Umbrina cirrosa* (Sandifer *et al*. 1993; Jirsa *et al*. 1997; Segato *et al.* 2005; Chatzifotis *et al.* 2006). Because the previous studies were conducted at small scale and for a relatively short time, the authors warned that growth rates of *T. macdonaldi*, *C. othonopterus*, and *C. parvipinnis* in low salinity may be susceptible of improvement by using infrastructure of greater size and culturing fish preferably to market size. Therefore, a set of results on growth of *T. macdonaldi* reared to a larger size in low salinity (12 g L^{-1}) and in seawater (36 g L^{-1}) is presented below. The data represent the first report on growth of *T. macdonaldi* in low salinity to what may be considered ready-for-sale size in certain niche markets. The study was conducted at CREMES, Kino Bay, Mexico, using fish produced at this hatchery, which

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were cultured in a recirculating aquaculture system for 115 days. Figure 3 shows growth of fish and mean water temperature. Body weight of fish cultured at low salinity slightly surpassed those held in seawater, in agreement with previous observations for this species (González-Félix *et al.* 2017). Many individual fish reached over 1 kg of weight at both salinities. On average, from an initial body weight of approximately 400 g, fish reached close to 900 g in 115 days of culture.

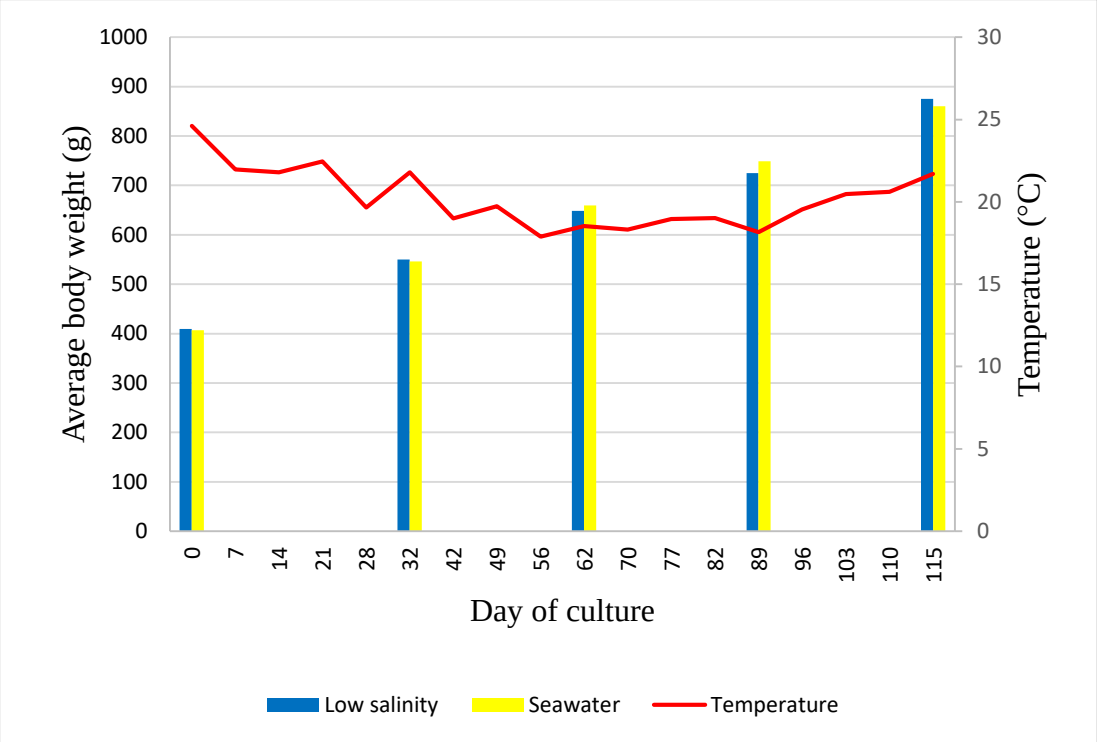

Figure 3. Growth of totoaba (*Totoaba macdonaldi*) reared for 115 days in a recirculating aquaculture system at low (12 g L^{-1}) and seawater salinity (36 g L^{-1}).

Growing at such rates, it is very likely that, if reared for a full year, fish could have matched the 2.5 kg of annual growth rate reported by Juárez *et al*. (2016) for totoaba held in seawater cages. Fish grown at low salinity were identical to the saltwater-reared counterparts and did not show any organoleptic differences after cooking. These results are definite proof that totoaba can be cultured to marketable size in low salinity.

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V-Conclusions

The Sciaenidae is a highly diversified family of fish with a remarkable ability to withstand salinity changes. So far, the body of evidence gathered related to their culture in low salinity, in terms of the high number of species and their diverse geographical distribution, is overwhelming. In Mexico, with the advent of commercial seawater culture of totoaba in the Gulf of California, the herein presented proof that this species can be also grown to marketable size at low salinity provides opportunities for culture in a variety of water sources, such as brackish or diluted saltwater, rivers, dams, or ground waters, perhaps in locations in which commercial culture was not previously thought possible. Together with the available evidence of low-salinity tolerance of the Gulf corvina, *C. othonopterus*, and the shortfin corvina, *C. parvipinnis*, this information opens possibilities for advancing the knowledge concerning low-salinity culture of more representatives of the many species of sciaenids found in Mexico.

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