Chapter 1

Overview on Status and Technological Advances in Tuna Aquaculture Around the World

Daniel D. Benetti[1], Gavin J. Partridge[2,3] and John Stieglitz[1]
[1]*University of Miami, Rosenstiel School of Marine and Atmospheric Science, Miami, FL, USA,* [2]*Australian Centre for Applied Aquaculture Research, Challenger Institute of Technology, Fremantle, WA, Australia,* [3]*Freshwater Fish Group & Fish Health Unit, School of Veterinary & Life Sciences, Murdoch University, Murdoch, WA, Australia*

1.1 INTRODUCTION

Advances in Tuna Aquaculture is the first book that encompasses all aspects related to this industry and it merges them into a state-of-the-art compendium that points the reader in the right direction, whether a science student, a researcher, a fisherman, or a farmer. It presents developments in tuna aquaculture throughout the world, from ranching wild juvenile fish to closed-cycle cultivation of a variety of tuna species with a focus on the high-value bluefin species. Reputed experts in their fields provide detailed accounts of the various disciplines directly or indirectly associated with tuna aquaculture. This introductory chapter summarizes the content of the book and provides an outlook for the future of the industry.

Tuna are some of the best-known and highly regarded species of fish. While "tuna" refers to a large number of scombrid species including skipjacks (SJT), bonitos, bullets, and frigates, most people associate the term with the large, high-value species of the genus *Thunnus* such as bluefin, yellowfin, and bigeye tuna that roam the world's oceans. Serving important ecological roles as both predator and prey, depending on the life stage of the fish, these species are now some of the most sought after marine fish for the global seafood market. The high market value of tuna stocks has led to intensified fishing pressure that, in turn, resulted in drastic population reductions in every ocean where these fish are found. High prices sustained by strong market demand also create opportunities for tuna ranching, which is

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arguably the most profitable form of fish farming in the world. Today, the practice of tuna ranching occurs at the intersection between the aquaculture and fisheries sectors which makes it difficult to consider them independently from each other. Complicating the issue is the fact that ranched tuna are typically fattened using wild-caught small pelagic fish species such as sardines and mackerel, as opposed to balanced diets, which is the case for the grow-out of other marine fish. With aquaculture now providing over half of the seafood consumed in the world, and future forecasts predicting consistent growth in global fish farming, it comes as no surprise that efforts to mass-produce tuna are following this trend.

Tuna industry stakeholders, from fishermen, farmers, and scientists to seafood business professionals and consumers, face enormous challenges and uncertainties when considering the sustainability of this industry. In an effort to better understand these issues and effectively manage the world's tuna stocks, five regional intergovernmental fisheries organizations—the Inter-American Tropical Tuna Commission (IATTC), the Western and Central Pacific Fisheries Commission (WCPFC), the Commission for the Conservation of Southern Bluefin Tuna (CCSBT), the Indian Ocean Tuna Commission (IOTC), and the International Commission for the Conservation of the Atlantic Tunas (ICCAT)—study tuna populations and the biotic, abiotic, and anthropogenic factors that influence these fisheries. In the present book, renowned scientists from both IATTC and ICCAT discuss important management challenges, as well as those brought about by the shift from traditional tuna fisheries to fattening (i.e., ranching) and farming, in Chapters 2 and 3.

While tuna fishing has been practiced for several millennia, tuna aquaculture is a relatively new industry. Although early tuna aquaculture efforts date back to the late 1960s, it was not until the early 1990s that industrial-scale ranching and farming developed into the modern industry that it is today. Similarly, research into closed-cycle aquaculture production of tuna began in the 1970s. However, due to the many challenges associated with hatchery production, the rewards of this protracted effort are only now being realized, with significant numbers of hatchery produced juveniles currently being put to sea, predominantly in Japan and to a smaller extent in Europe. The accomplishments by Japanese scientists, which represent an important milestone, have led to advances in hatchery technology throughout the world, and have made closed-cycle tuna production a reality.

It is difficult to accurately report on total global catches and farmed tuna production. Even data reported from the most credible and reputable sources are incomplete, contrasting, and often conflicting. This is reflected, to a great extent, throughout the different chapters of this book. According to the latest fisheries statistics available, catches of tuna and tuna-like species continue to increase and set a new record at more than 7 million metric tons in 2012 (FAO, 2014). However, the majority of this catch comprised low-value skipjack, primarily sold to the canning industry. Seven species have consistently accounted for about 90% of the total tuna catch since 2000. Catches of small tuna (such as skipjack, frigate, and bullet tuna), seer fishes (*Scomberomorus* spp.), and albacore have grown significantly. In 2012, catches of yellowfin tuna exceeded the 2000 level, after fluctuations in prior years, while bigeye tuna had the only decreasing trend with catches down by 5% (FAO, 2014).

The total volume of the higher value, fresh or frozen product destined primarily for the sashimi market, is approximately one-third of the total. The actual quantity of tuna produced via aquaculture is difficult to accurately quantify, and there is great disparity among the figures quoted by the various reporting agencies and governments. The reasons for these discrepancies are described in detail in a recent paper by Metian et al. (2014). The data from the FAO in Table 1.1 suggests that the annual global aquaculture production of bluefin tuna in the years between 2011 and 2013 ranged from ca. 9400 to 23,500 metric tons, however, this dataset omitted the production from several countries and underreported production from others. For example no production was included for Japan in 2011, the Australian production was underreported and the production of ABFT was listed as only ca. 3000 to 4000 metric tons, despite a TAC of ca. 13,000 metric tons during this period. We believe a more accurate estimate of the current total bluefin aquaculture production is that provided by Tveteras et al. (2015) of

TABLE 1.1 **Aquaculture Production (metric tons) of Pacific, Southern and Atlantic Bluefin Tuna as Reported by the FAO**

Country	Species	2011	2012	2013
Japan	PBFT		9639	10,396
Mexico	PBFT	3557	1784	6228
Australia	SBFT	1987	2486	3482
Croatia	ABFT	1610	1125	915
Spain	ABFT	575	555	305
Malta	ABFT	960	530	985
Turkey	ABFT	100	395	470
Tunisia	ABFT	70	220	630
Italy	ABFT	435	85	85
Greece	ABFT	95	30	55
Total		9389	16,849	23,551

Source: FAO (FishStat).

TABLE 1.2 Aquaculture Production (metric tons) of Pacific, Southern and Atlantic Bluefin Tuna in 2014 as Reported by Tveteras et al. (2015)

Region	Species	2014
Japan	PBFT	9000
Mexico	PBFT	4500
Australia	SBFT	8350
Mediterranean	ABFT	14,500
Sum		36,350

ca. 36,000 metric tons (Table 1.2). Tuna aquaculture production currently comprises only the three highly regarded bluefin species, namely, Pacific bluefin tuna (PBFT, *Thunnus orientalis*), Atlantic bluefin tuna (ABFT, *Thunnus thynnus*), and southern bluefin tuna (SBFT, *Thunnus maccoyii*). PBFT is cultured in Japan and Mexico, ABFT in several countries bordering the Mediterranean Sea, and SBFT only in Australia. While yellowfin tuna (YFT, *Thunnus albacares*) has previously been cultured in Mexico and Oman (see Chapter 8), there is currently no aquaculture production of this species. However, this is changing rapidly, as we are currently witnessing breakthroughs with YFT hatchery technology (Chapter 5).

Production volumes of bluefin tuna vary considerably between species and the regions in which they are grown, and also over time as catch quotas change. For recent years, indicative figures are summarized in Tables 1.1 and 1.2. While Japan is now the largest producer, this is a recent occurrence, and the production of Japanese farmed PBFT only exceeded that of ranched SBFT and ABFT in recent years (Tada, 2010).

As described throughout this book, the vast majority of tuna aquaculture production is still reliant upon the capture of wild-caught juveniles. This production is referred to as ranching, fattening, or farming, and these terms are often used interchangeably. In the true sense, however, ranching and fattening differ from farming. The former two terms are more accurately applied to the short-term practice of holding subadult or adult tuna primarily for the purposes of increasing condition and fat content, thus improving their market value. However, significant increases in biomass are often also achieved. This is the practice employed in Australia and Mexico, and by the majority of Mediterranean producers. The ranching or fattening period differs between regions but typically only lasts up to several months. The use of such fattening practices has grown exponentially in the last decade, to the point where today, a large proportion of all bluefin tuna caught in many parts of the world are stocked into cages for increasing their size and fat content prior to being sold. In spite of the inherent issues of the operation (they are fed sardines and other forage fish which are ecologically very important), this practice could be considered a "value-added" process, since the individual value of the tuna kept in the cages increases considerably in what can be viewed as a more energetically and ecologically efficient way than would occur nature. Farming involves the capture of juveniles which are then held for extended periods of up to several years. Farming of wild-caught juvenile tuna occurs only in Japan and Croatia, although preadults are also caught and grown in Mexico as they migrate across the Pacific Ocean. The more recent practice of growing hatchery reared juveniles is also termed "farming." While we have attempted to apply these terms consistently throughout this book, the term "farming" is often applied as a generic term to all of these practices.

The boom in the tuna farming industry over the last 25 years has been predominantly driven by the high prices achieved in Japan, where some 400,000−500,000 metric tons of tuna are consumed annually, primarily as sashimi and sushi (OPRT, 2015) (Figure 1.1).

FIGURE 1.1 (A) Toro, the fattest, finest, and most expensive bluefin tuna sashimi in the world; (B) Maguro, also greatly appreciated in the sashimi market worldwide, especially in Japan; (C) Increased demand for high-quality tuna for sashimi and sushi markets in Japan and elsewhere is driving the exploitation of their fishery stocks and efforts to develop close-cycle aquaculture. *Photos: Daniel Benetti.*

Exorbitant and headline-making prices are often paid for bluefin at the first auction of the season at the Tsukiji, Nagoya, and Osaka markets. However, average prices are significantly less. While the current record price for a bluefin stands at US$1.763 million for a 222 kg PBFT (equating to nearly 8000 USD/kg), the average prices for bluefin range widely from approximately 7–100 USD/kg, with high-grade tuna currently ranging from 40 to 100 USD/kg and low-grade from 10 to 20 USD/kg. Fernandez-Polanco and Llorente describe in Chapter 14 that the market in Japan is currently stagnating or slightly decreasing, yet the explosion in the popularity of Japanese cuisine throughout the rest of the world has continued to sustain demand. The history and current status of the farming and hatchery production of the main tuna species are summarized below.

1.2 PACIFIC BLUEFIN TUNA

Japan's farming history is described in Chapter 7. While it dates back to the 1970s, these early attempts were aimed at capturing immature fish and growing them to maturity to be used as broodstock. Commercial-scale farming did not begin until the early 1990s, with the first harvest of some 900 metric tons occurring in 1993 (Tada, 2010). As previously described, PBFT in Japan are farmed rather than ranched, and the methods therefore differ from the ranching of other species and regions. The main difference lies in the fact that early juvenile PBFT weighing only 100–500 grams are stocked and grown to a market size of 30–50 kg over a period of 2–3 years (Masuma et al., 2008). Farmed tuna production in the late 1990s and the early years of the 2000s ranged from 2000 to 7000 metric tons/annum (Tada, 2010). It was not until 2010 that the Japanese Ministry of Agriculture, Forestry and Fisheries (MAFF) introduced mandatory reporting requirements for Japanese tuna farmers (Koya, 2010), and these more recent production figures, which now exceed 9000 metric tons/annum, are detailed in Chapter 8. In 2012, MAFF reported a production of 9592 metric tons (similar to that reported by the FAO in Table 1.1), of which 244 metric tons were derived from hatchery-reared juveniles. Presumably these were the juveniles harvested from the first large-scale commercial stocking of ca. 45,000 hatchery reared juveniles in 2009 (Tada, 2010).

The evolution and advances in hatchery technology for PBFT since 1970 are also described in Chapter 7. These developments have been driven primarily by Kinki University (now known as Kindai University) with the federal government (Fisheries Research Agency), prefectural governments, and private companies also playing important roles. Egg production from PBFT in Japan is derived almost entirely from naturally spawning fish held in sea cages, with the first land-based broodstock system only recently commissioned in Nagasaki in 2013. The development of hatchery technology has been a very challenging road, with significant mortality

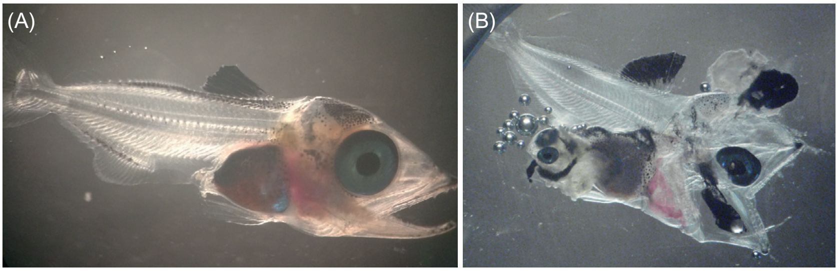

FIGURE 1.2 (A) During the third week post-hatch, yellowfin tuna larvae have large mouths, well-developed eyes and teeth, and begin their piscivorous stage, becoming extremely aggressive and cannibalistic. (B) Gut analysis of a 15-day post hatch (15 DPH) yellowfin tuna larvae showing another larvae of the same batch in the gut. All tuna species are highly cannibalistic. *(A) Photo: Craig Purcell, (B) Photo: Zack Daugherty.*

events occurring during every life stage. These can be summarized as (i) floating death and sinking death during the first 8 days of life (Ishibashi, 2010), (ii) cannibalism and collision death during the post-flexion stages, and (iii) transfer-related mortalities after they are moved from land-based hatcheries to sea cages. Mortality rates during each period can approach 90% and the overall average survival of tuna larvae ranges from 0.01% to 4.5% (Masuma et al., 2008). Feeding tuna larvae also represents a challenge not experienced in the culture of other marine fish, as they must be fed on the yolk-sac larvae of other marine fish, with feeding on *Artemia* alone resulting in "growth failure" (Seoka et al., 2007). Arguably, cannibalism remains the most serious problem causing low survival rates of all species of tuna larvae (Figure 1.2).

As is described throughout this book, these same challenges have also been experienced in all other tuna species reared to date. The life cycle of PBFT was closed by Kinki University in 2002, with the first successful spawning of first generation broodstock (Sawada et al., 2005). Between 2002 and 2007, approximately 10,000 juveniles per year were produced, and in 2009 this increased to 45,000 (Tada, 2010). The outlook from recent MAFF reports for the increasing contribution of hatchery reared tuna to the total tuna production is positive, as they report that in 2012, 56% of the 474,000 juvenile tuna stocked in cages were hatchery produced. Large commercial companies such as Maruha Nichiro and Nippon Formula Feed Manufacturing Company, among others, have invested in tuna hatcheries and are now producing commercial quantities of juveniles (Masuma et al., 2011).

Progress in PBFT hatchery production has also been reported from South Korea with several thousand PBFT juveniles having been produced at the Future Farming Research Center of the National Fisheries Research and Development Institute (NFRDI), the Jeju Ocean and Fishery Institute, and Gyeongsangnam-do Fisheries Resources Research Institute. The juveniles are being grown in SeaStation submersible sea cages in high-energy sites off Jeju Island, where the occurrence of typhoons is a significant challenge to the success of the grow out industry.

Mexico produces the second largest volume of ranched PBFT after Japan and this industry is also described in Chapter 8. Mexican tuna farms exploit the same stock of PBFT as the Japanese, as the fish migrate across the Pacific Ocean. Ranching in Mexico follows similar methods to those used in Australia and the Mediterranean. There have been no attempts in Mexico at PBFT hatchery production.

1.3 ATLANTIC BLUEFIN TUNA

Farming of the eastern stock of ABFT occurs in several countries which border the Mediterranean Sea and the Atlantic coast of Portugal, and has occurred on an industrial-scale since the mid-1990s after beginning in Spain in 1979 (Ottolenghi, 2008). The tenuous state of wild ABFT stock in the eastern Atlantic has been the subject of much controversy and quota restrictions and is well documented throughout this book.

ABFT for ranching are targeted by purse-seiners and traditional trap fishermen during their spawning migrations, and typically range in size from 40 to 400 kg (Figure 1.3). Fish targeted for farming in Croatia range from 8 to 30 kg. The fattening period in the Mediterranean ranges from 3–7 months, and the farming period in Croatia lasts up to 2 years (Mylonas et al., 2010). As with all ranching operations, production is closely linked to the quotas placed on the wild stocks, and this is discussed in detail in Chapters 3 and 6.

In an effort to reduce the reliance on wild-caught juveniles and enable consistent supply, there has been an intensive effort on closing the life cycle of ABFT in Europe since the early 2000s. The European Union has invested in excess of €10 million in major R&D consortiums such as

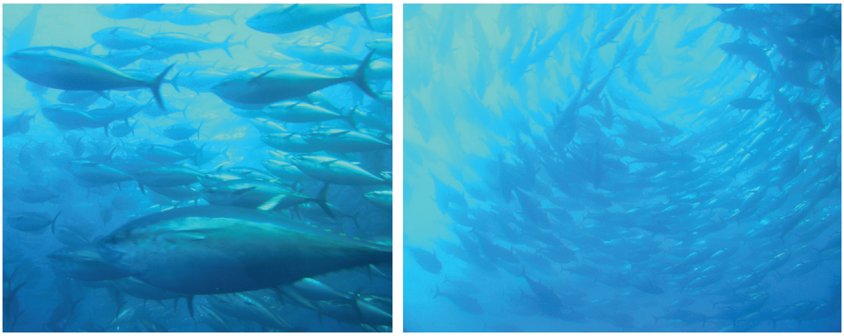

FIGURE 1.3 Atlantic bluefin tuna cultured in cages in the Mediterranean. *Photos: Valerio Vitalini and Daniel Benetti.*

the REPRODOTT and SELFDOTT, with considerable funding from other European governments and companies. There has been a strong collaborative focus during these projects, which has yielded excellent outcomes in terms of both pure science and the important applied outcome of juveniles put to sea. These outcomes and achievements are described in detail by Karakulak et al. and de la Gandara et al. in Chapters 4 and 6, respectively. Egg production has again been heavily reliant on broodstock held in cages, both from natural spawning and hormone induction techniques using a variety of specialized sustained release hormone implants (primarily GnRH-a). Spawning induction using this practice has led to remarkable improvements in the quantity of eggs collected and in extending the captive-spawning season to over 2 months instead of only a few weeks. These techniques are described in detail in Chapter 7. The largest land-based bluefin tuna broodstock facility in the world has recently been completed at the Spanish Institute of Oceanography (IEO) in Mazarron, Spain, and is described in Chapter 6. This facility will allow ABFT to be spawned in captivity under controlled conditions, and represents a significant advancement in the closed-cycle production of this species. In 2011, the IEO put some 3000 juvenile ABFT to sea and these are now approaching maturity.

Great progress is also being reported from Cyprus and Turkey: Kiliç Seafood Co., the largest producer of sea bream and sea bass in Europe, has recently begun developing hatchery technology and grow out of ABFT in the Aegean Sea. In 2014–2015, the company successfully produced 15,000 juveniles from eggs collected from its own broodstock cages. Juveniles weighing 5–10 grams were transferred to nursery cages and as of the time of this publication, a total of 1000 fish weighing approximately 10 kg at 420 days post hatch remain.

Europeans are therefore on the verge of closing the life cycle of ABFT as has been achieved with PBFT in Japan.

1.4 SOUTHERN BLUEFIN TUNA

The ranching of SBFT is described in detail by Ellis and Kiessling in Chapter 9. South Australia is the only place in the world where SBFT are farmed, despite several other countries also owning quota. Total global quota of SBFT has been diminishing since the introduction of quotas in 1989. In 2014, however, CCSBT's Scientific Committee reported that the wild stocks of SBFT have been recovering, and the global TAC was increased from the 9449 metric tons set in 2010 to 12,449 metric tons in 2014 and to 14,647 metric tons for the period 2015–2017. Australia's share of the global TAC between 2015 and 2017 will be 5665 metric tons, the highest since 1989.

Ranching of SBFT in Australia involves the purse-seining of subadult fish in the Great Australian Bight, which are then towed into the ranching sites in the waters surrounding Port Lincoln. At this stage in their migration, the fish are approximately 2 years old and weigh around 15 kg. They are fattened for 6−9 months on local and imported baitfish, during which time they increase in size to 30−40 kg. Approximately 20% of the harvested product is flown fresh to Japan, with the remainder shipped frozen.

Efforts to close the life cycle of SBFT have been driven by one Australian company, Clean Seas Tuna (CST), with funding support from the Australian Federal Government. These efforts are described by Chen et al. in Chapter 10. In summary, CST's tuna propagation program began in 1999 with approximately 500 of their farmed stock being retained in sea cages for on-growing as future broodstock (Stehr, 2010). CST built the world's first land-based broodstock system for any bluefin species in 2006, and some of the retained fish were transferred from the sea cages to the broodstock tank via helicopter (Partridge, 2013; Stehr, 2010). Closing the lifecycle of SBFT presents additional challenges compared to similar efforts with ABFT and PBFT. While the latter two species mature at 3−5 years and ca. 50−60 kg (Masuma et al., 2008; Ottolenghi, 2008), SBFT mature somewhere between 8 and 14 years at sizes in excess of 100 kg. Despites this challenge, CST first achieved successful spawning from hormone-induced broodstock in 2008 (Thomson et al., 2010). In 2009, approximately 50 million eggs were produced (Stehr, 2010). Juveniles were successfully reared on land to an age of 238 days and *Time Magazine* named CST's "Tank-Bred Tuna" the second best invention of the year. The first successful transfer of 149 juvenile SBFT to the sea was achieved in 2011. However, after growing to a size of ca. 500 grams, they succumbed to South Australia's cold winter water temperatures (CST, 2012a). It was planned to advance the spawning season in subsequent years in order to enable larger and more robust fish which could tolerate the low winter water temperatures to be put to sea. While some advanced spawning events were achieved in the controlled environment broodstock tank, the results were poor in terms of the number of fertilized eggs produced (Chapter 10). In 2012, CST announced the suspension of its SBFT propagation program in order to focus their efforts and resources on their yellowtail kingfish operation (CST, 2012b). The broodstock have been retained in the hope of restarting the program at some point in the future (CST, 2015).

1.5 YELLOWFIN TUNA AND OTHER TUNA SPECIES

Although the value of YFT is less than that of bluefin tuna, there is still considerable interest in the aquaculture of this species. It is in Mexico that the majority of attempts to ranch YFT have been made, but as described in Chapter 8, problems have arisen primarily due to availability of suitably sized wild stock, rather than issues regarding their biological or technical suitability for ranching. Hatchery production of YFT would overcome these issues and as described in detail in Chapter 5, great progress is being made toward this goal.

YFT grow rapidly, mature at an earlier age, smaller in size than bluefin, and spawn readily in captivity nearly year-round and without hormone induction. Research into hatchery production of YFT has been undertaken primarily at the Inter-American Tropical Tuna Commission's (IATTC's) laboratory in Panama, and, to a lesser extent, at the Gondol Research Institute for Mariculture (GRIM) in Indonesia. Both land-based broodstock facilities were constructed in collaboration with the Japanese Overseas Fishery Cooperation Agency (OFCF). While the focus of the work at the IATTC has been primarily to gain a better understanding of the ecology of this species in the wild, many of their findings have direct relevance to commercial hatchery production of both YFT and the bluefin species. Recent research collaboration between the IATTC, Kinki (Kindai) University, and the Autoridad de los Recursos Acuáticos de Panamá (ARAP) has advanced the science of both YFT and PBFT through comparative studies of these two species. As part of this research, many notable achievements have been made including the recent transfer of the first juvenile YFT to an experimental floating sea cage for grow out off the Pacific Coast of the Republic of Panama. Worldwide, this represents the first successful transfer of hatchery-produced YFT juveniles to a sea cage. The juveniles stocked in the sea cage ranged in length from 9 to 13 cm, and were raised from fertilized eggs spawned by captive YFT broodstock kept at the ARAP/IATTC Achotines Laboratory in Panama. This achievement marks an important milestone toward closed-cycle production of this species and increased understanding of the later life stages of YFT in captivity.

Unlike the IATTC facility, GRIM in Indonesia has a focus on commercial aquaculture production. Since beginning operations in 2003 it has, however, received intermittent funding, which has hampered its ability to continuously retain broodstock and therefore sustain spawning. The occurrence of the egg protozoan parasite described in Chapter 11 and by Hutapea and Permana (2007) has also hampered larval rearing efforts, and the oldest juvenile produced at GRIM has been 53 days of age. Aside from the challenges faced by the tuna research program at GRIM, much progress has been made in the development of capture, transport, and acclimation of YFT to the land-based holding facilities. The GRIM facilities and their achievements are described in detail by Partridge (2013), Hutchinson et al. (2011), and Hutapea et al. (2009).

A number of other research and development projects have occurred in the past few decades examining the feasibility of closed-cycle production of other tuna and tuna-like species such as the bigeye tuna (*Thunnus obesus*),

FIGURE 1.4 Blackfin tuna (*Thunnus atlanticus*) metabolism and swimming energetics studies are providing the basic scientific information required to develop sound aquaculture technologies for this species in the near future. *Photo: John Stieglitz.*

blackfin tuna (*Thunnus atlanticus*), and bonito species (Atlantic: *Sarda sarda*; Pacific: *Sarda chiliensis*). These species, while not as well-known as bluefin and yellowfin tuna, are nonetheless valuable to the fishing industry. Given the smaller size of blackfin tuna and bonito, these species are easier to transport and maintain in smaller land-based facilities compared to the infrastructure involved in maintaining bluefin or yellowfin tuna broodstock in land-based tanks. In the case of the bonito species, the life cycle has been closed on an experimental scale (McFarlane et al., 2000; Ortega et al., 2013).

Blackfin tuna is the smallest of the true tuna species of the genus *Thunnus*, reaching 1 m and 20 kg within a relatively short life span of 5 years. While it is unlikely that blackfin tuna will ever compete in the same global marketplace of its larger counterparts, as a true *Thunnus* species it deserves attention for commercial aquaculture development, targeting another segment of the market—a smaller size, yet high-quality, sashimi-grade tuna. Attempts to spawn blackfin tuna in land-based tanks have not been successful thus far (Benetti et al., 2009). Despite ongoing research efforts investigating their bioenergetics (Figure 1.4), spawning this species of tuna in captivity remains challenging.

1.6 HEALTH, NUTRITION, AND GENETICS

While Balli and colleagues describe in Chapter 11 a wide range of diseases (and particularly parasites) that have been found in tuna, it is also clear from this chapter that tuna are remarkably robust and have not suffered a great deal from acute or chronic mortalities associated with disease outbreaks. Indeed, many of the parasites hosted on the wild-caught fish introduced to ranching are lost once they are held in cages. These authors also effectively point out, however, that more diseases are likely to be encountered as farming intensifies and once the life cycle of more species are closed and naïve fish are put to sea.

With consistent growth in the global demand for high-value tuna comes a need to develop cost-effective and environmentally sustainable methods to satisfy this demand. Given that feeds comprise, on average, over 60% of operating costs for tuna farming operations, research into tuna nutrition offers the potential to help offset the high costs involved in producing farm-raised tuna for the global market. The small pelagic fish (erroneously termed "trash fish"), still primarily being used to feed tuna in cages, are less expensive than formulated diets but have a significant ecological footprint. Consequently, its use is highly controversial and constantly challenged by some influential scientists and powerful environmental groups. Even though many believe that feeding small pelagics to grow tuna to market size is "value-added fisheries" (i.e., it is more ecologically efficient than the efficiencies that exist in the food chain in the wild), this ongoing practice is generally recognized as ecologically unsustainable, costly, and unpractical given the logistics required to obtain, transport, and handle the small pelagics from the fishing source to the feeding of the tuna in the cages. The obvious route will be to develop feed formulations that are more economically and ecologically efficient, and much progress is being made toward this goal, as reviewed by Buentello and colleagues in Chapter 12. There are many inherent qualities in tuna that make them challenging candidates for robust nutritional studies, yet as tuna culture expands globally, more nutrition research is being conducted on these high-value animals. Given the high-performance metabolism of tuna, and of scombrids in general, it is intuitive that high-energy diets have been found to be positively correlated with growth, survival, and food conversion ratios in such species. However, different species and different life stages of tuna possess specific nutritional demands, and one of the keys to unlocking the full aquaculture potential of these animals lies in gaining a better understanding of their physiological and nutritional requirements.

Finally, recent efforts to develop techniques for genetic improvement of PBFT through a novel breeding program at Kindai University in Japan are described by Sawada and Agawa in Chapter 13. The breeding program is targeting improved reproduction, increased survival and growth rates, disease resistance meat quality and yield. Ultimately, the program aims at the domestication of PBFT while maintaining genetic diversity to preserve the gene pool of natural populations in case of escapements. Although the breeding program has just begun, it is developing fast and requires the simultaneous implementation of a strategy for intellectual property protection in anticipation of potential conflicting issues in the future development of full-cycle tuna aquaculture technologies. Sawada and Agawa discuss these important topics in Chapter 13.

1.7 MOVING TO COMMERCIAL-SCALE HATCHERY PRODUCTION

The vast majority of tuna industry stakeholders now widely accept the view that aquaculture will play a key role in the future of tuna fishery stocks. However, to provide the economic stimulus for moving from wild-caught to hatchery-produced juveniles, the price of producing the latter should be cheaper than the cost of catching the former. While there appears to be no data on the current costs of producing juvenile PBFT in Japan, they are likely to be very high given the low survival rate and the high cost of maintaining tuna broodstock. Alternative technologies under investigation in Japan for overcoming the high costs of maintaining broodstock include the development of true surrogates in which smaller, highly fecund species such as mackerel could deliver viable tuna gametes, as has been conducted with other species (Masuma, 2010; Okutsu et al., 2007; Partridge, 2013). Other methods with potential include obtaining viable gametes from commercially farmed PBFT as they are being harvested for market and inducing early maturation (Elizur et al., 2009; Masuma, 2010; Endo et al., In Press).

While the number of hatchery-reared juvenile PBFT produced in Japan has increased rapidly in recent years, much of this increase can be attributed to the increases in the number of eggs used rather than dramatic improvements in larval survival. Figure 1.5 highlights the relationship between the number of eggs used and the number of juveniles produced. Although this graph shows different numbers of juveniles produced compared to those reported elsewhere in this book, these inconsistencies are likely the result of the high post-transfer mortality and therefore, the stage at which the assessment of the number of juveniles produced is taken.

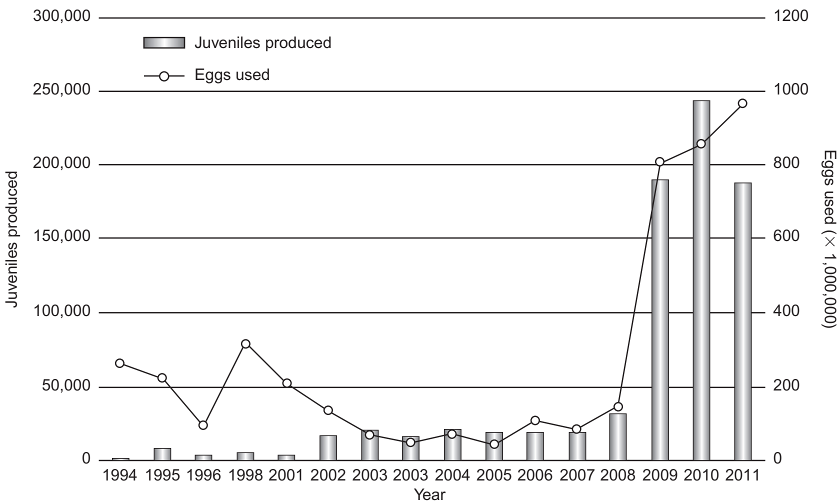

FIGURE 1.5 Relationship between number of eggs and juveniles production of Pacific bluefin tuna in Japan.

The reliance on increasing egg numbers to increase juvenile supply is a strategy that may be viable for early-maturing species such as PBFT and YFT, which may begin spawning during the normal farming period and which spawn in cages or relatively simple land-based systems. For species such as SBFT this strategy will not be as straightforward, as they mature at a much older age and do not undergo final maturation in the cool waters where they are currently ranched (Bubner, 2012).

A number of land-based bluefin broodstock facilities have recently been commissioned to control and extend the natural breeding season. While this will be an effective strategy to supplement the eggs collected from caged broodstock, land-based facilities may not provide sufficient eggs to produce commercial quantities of juveniles in their own right, unless concomitant and significant increases in hatchery and nursery survival rates also occur. For example, Figure 1.5 demonstrates that the production of ca. 250,000 juvenile tuna in Japan in 2011 was derived from an egg collection during that period of nearly 1 billion eggs. Obtaining such quantities of eggs only from land-based facilities may be cost-prohibitive. However, because of such high stakes and of the success of natural year-round spawns of YFT in captivity at IATTC's Achotines Laboratory in Panama, major efforts and investments have been made in Japan, Spain, Australia, and South Korea to build sophisticated land-based facilities to spawn bluefin tuna in captivity with or without the use of hormone implants. Results of these efforts remain uncertain to date, and egg collection from both PBFT and ABFT continue to be conducted successfully from natural and induced spawnings in cages (Figure 1.6).

FIGURE 1.6 Collecting Atlantic bluefin tuna naturally spawned eggs in a cage in Calabria, Southern Italy. Similar practices are carried out extensively wherever tuna are spawned naturally or through the use of hormone induction, including in Japan, Spain, Malta, and Croatia. *Photo: Daniel Benetti.*

To reduce the production costs of juvenile tuna, significant increases in survival rates will also be required, thereby leading to more stable and consistent production. A great deal of research is therefore still required to overcome the various bottlenecks that cause significant mortalities during each life stage which are described throughout this book. The development of effective early weaning diets will also greatly assist in overcoming the many disadvantages of feeding yolk-sac larvae, including the costs of maintaining separate broodstock populations and the risks of disease transmission (Masuma et al., 2011).

1.8 CONCLUSIONS

While fisheries management strategies will continue to play an important role in preserving wild tuna stocks at sustainable levels, it is clear that tuna aquaculture will be a crucial component of global tuna conservation. Closing the life cycles of the primary high-value tuna species will allow for more sustainable production to satisfy the world's insatiable demand. The fisheries trends for these species will likely follow that of the seafood industry as a whole, where aquaculture now produces more than half of the seafood for human consumption worldwide, and has recently surpassed global beef production in terms of annual production tonnage. In fact, aquaculture development is entirely reshaping the seafood industry and fisheries management strategies worldwide. It is reasonable to assume that tuna production will follow this trend. At the current pace, fattening practices combined with closed-cycle tuna aquaculture clearly have the potential to supersede wild capture production of bluefin tuna in the near future as well. While critics question the ecological sustainability of raising carnivorous pelagic species such as tuna, ingenuity, and economic drivers ensure that the industry will develop in the right direction. This argument has become increasingly important amidst strict regulations aimed at curbing the harvest of wild tuna, as seen in recent bans on yellowfin tuna fishing and calls for bans on international trade of bluefin tuna and for their inclusion in the red lists of influential environmental groups and NGOs that shape public opinion and government policy.

However, such progress will not come easily given that some aspects of tuna aquaculture remain controversial. For instance, when it comes to capture-based aquaculture, which comprises the majority of current tuna farming efforts, serious problems arise in the quantification of such production as the size of the tuna is only estimated when they are initially stocked in the cages. This practice has the potential to cause significant uncertainty in the fishery statistics. Previously, there was no documentation for the trade of live tuna, allowing for the proliferation of IUU (illegal, unregulated, and unreported) fishing (Miyake, 2003). Other criticisms include those normally associated with traditional aquaculture operations, such as, excess feeds and waste entering the water.

Furthermore, the demand for small pelagics to feed tuna in the cages continues to grow and the majority of these fish come from fishery stocks outside the tuna on-growing regions. Such practices add further ecological and economic costs to the environmental footprint of the operations, and legitimize criticism from opposing NGOs and other stakeholder groups. However, one might argue that even under the most adverse circumstances, such as capturing juveniles for stocking cages and feeding them with small pelagics, the practice of tuna fattening could still be considered a value-added fishery. This is because captive tuna convert feeds more efficiently than their wild counterparts, largely as a result of the lower metabolic cost of a captive lifestyle, and the added fat increases the quality and value of the final product. Additionally, this practice allows tuna to be harvested in response to market demand, while also providing better usage of the biomass captured within strict tuna quotas since cumulative biomass is increased without a concurrent increase in mortality and fishing effort. As previously pointed out, we reiterate that tuna fattening blurs the line between traditional fisheries and aquaculture operations, and this intersection provides ample opportunity for future research into the economical and ecological impacts of the industry. This is further discussed in Chapter 3.

Nonetheless, most stakeholders, including this book's editors and authors, concur that closing the life cycle of high-value tuna species in captivity to provide juveniles for stocking grow out cages combined with the development of practical diets to reduce reliance on small pelagics for feeding the fish are necessary steps to ensure the sustainable expansion of the industry. These goals have been recognized by governmental agencies throughout the world and a great deal of effort is being carried out in numerous countries throughout Europe, the Americas, Australia, and Asia to develop hatchery technology and aquafeeds for tuna. This book details many of these efforts, while providing a roadmap for the future development of the tuna aquaculture industry. As the ink dries on the pages within, considerable progress in this industry is being made throughout the world. Undoubtedly, by the time this book goes to press, additional important breakthroughs will have happened. Tuna aquaculture is a rapidly developing field, and it is predicted that advanced technologies from hatchery to market will dramatically improve fisheries and aquaculture practices to ensure the future of tuna as a sustainable resource in the decades to come.

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