Advancing production of marine fish in the United States: Olive flounder, *Paralichthys olivaceus*, aquaculture

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**Abstract**
The potential for marine aquaculture development in the United States is significant and recent factors have highlighted the benefits of developing a shortened seafood supply chain to service domestic markets. Marine finfish in particular hold tremendous potential as technological advancements, improvements in production efficiencies, and market forces have aligned to create opportunities for growth within this sector of the aquaculture industry. Olive flounder, *Paralichthys olivaceus*, also commonly known as the Japanese flounder or *hirame*, is a candidate species for the U.S. aquaculture industry, which has a demonstrated track record of culture success and high market value. Although cultivation of the species is novel to the United States, olive flounder has been produced commercially for decades in other regions, notably Korea and Japan. With a number of favorable production characteristics, including a relatively short growout time compared with other flatfish species, an efficient food conversion ratio, and a well-established market presence, the species has been shown to be commercially viable. This study examines the opportunities for olive flounder to be developed in the United States, while also discussing the potential for land-based recirculating aquaculture systems culture of this species in...
Development of commercial-scale marine fish aquaculture in the United States has faced many challenges over the past decades. Regulatory, environmental, social license, technological, and market-based factors, among others, have all played a role in impeding development of marine aquaculture in the United States. However, there is a growing consensus that marine aquaculture in the United States is entering a new era with a promising future. Supporting this notion are factors including the rise in human population, the increase in per capita seafood demand, and a mounting seafood trade deficit, which all create a tailwind of support for increasing domestic seafood production in the United States (Kite-Powell, Rubino, & Morehead, 2013). Wild-caught fisheries production has largely plateaued both globally and domestically, with many forecasting further declines in the future as a result of climate change and increased degradation of wild fisheries habitats (FAO, 2020). Aquaculture has numerous production advantages for supplying the majority of seafood for human consumption, as evidenced in the market whereby aquaculture supplies over half of the seafood consumed by humans worldwide (FAO, 2020). Despite being one of the world’s largest terrestrial agriculture producers and having more sovereign seawater resources than any other country on earth, the United States ranks 17th in global aquaculture production (NOAA - NMFS, 2020). Expansion of marine aquaculture in the United States unquestionably holds the most potential, compared to freshwater aquaculture expansion. Freshwater resources are of increased value worldwide and are much more limited in availability when it comes to water that is accessible for human food production (Boretti & Rosa, 2019). Globally, most marine finfish aquaculture takes place in coastal and offshore waters, with a general trend toward moving further offshore to realize the production advantages associated with offshore aquaculture. However, efforts within the United States to expand marine aquaculture in coastal and offshore waters have faced significant public resistance along with numerous regulatory and logistical challenges (Knapp & Rubino, 2016; Lester, Gentry, Kappel, White, & Gaines, 2018). Such headwinds have led many to turn to land-based marine finfish production as a means to capitalize on the opportunities associated with domestic seafood production while avoiding many of the challenges involved with attempting to do so in a coastal or offshore farming scenario.

Land-based marine finfish production can generally be broken down into three farming methods: (1) coastal ponds with little or no water exchange, (2) flow-through coastal farms using ponds and/or tanks, or (3) recirculating aquaculture systems (RAS). Although Methods #1 and #2 are commonly used for aquaculture production in other parts of the world, coastal real estate in the United States is typically in high demand for other non-aquaculture purposes and is priced at a level above which would make Methods #1 and #2 economically viable. Therefore, when it comes to land-based marine finfish production in the United States, RAS aquaculture has been identified as one of the most promising farming methods (Tal et al., 2009; Zohar et al., 2005). There are pros and cons to utilization of any aquaculture production method. In the case of marine RAS, the challenges have historically outweighed the benefits and the fact remains that there have been few, if any, marine RAS production facilities in the United States that have proven to be economically viable over time. Many look to the burgeoning land-based salmon RAS movement in the United States as evidence of a sea change in the industry, yet due to the nascent stage of this segment of the industry it is still too early to declare any of these operations economically viable. In addition to land-based salmon production, producers and investors have been exploring the potential for other promising marine finfish species that
may be able to capitalize on the benefits associated with RAS production while limiting the significant risk associated with developing novel species for the aquaculture sector. One species that is well established globally and an ideal candidate for the U.S. land-based aquaculture production is olive flounder, *Paralichthys olivaceus*, also commonly referred to as the Japanese flounder, *hirame*, or bastard halibut. This species has a well-established global market, including in the United States where the species is sold primarily live in Asian markets or in the numerous sushi and sashimi restaurants that have expanded around the United States.

### 2 | OVERVIEW OF OLIVE FLOUNDER AQUACULTURE

Olive flounder is native to the Western Pacific ocean from the Kuril Islands of Japan to the South China Sea (FAO - Species Fact Sheets, 2021). Historically the world’s largest producers of farm-raised olive flounder have been the Republic of Korea (“Korea” hereafter) and Japan, with aquaculture production of 37,250 and 2,200 m.t. live weight, respectively, in 2018 (FishStatJ - FAO Fisheries and Aquaculture Software, 2020). China also produces significant amounts of farm-raised olive flounder, which comprise a portion of the reported 57,567 m.t. of farm-raised left-eyed flounders produced in China in 2018 (FishStatJ - FAO Fisheries and Aquaculture Software, 2020; Gui, Tang, Li, Liu, & Silva, 2018). Most of the aquaculture production of olive flounder is currently land-based in these countries. Since flounder are a benthic species that prefer to spend time congregated together on the bottoms of holding basins, ocean-based rearing in net pens has proven challenging. Additionally, regions where ocean-based farming of flatfish species is conducted typically encounter winter water temperatures, which result in significantly extended growout times compared with land-based olive flounder production areas, such as the operations on Jeju Island, Korea, that experience more stable year-round water temperature regimes (Furuta, Kikuchi, Iwata, & Honda, 1998). The land-based production is primarily flow-through at most commercial farming facilities in Japan and Korea, with incoming seawater typically undergoing various levels of mechanical filtration and sterilization prior to use in the culture tanks. A large amount of seawater from coastal sources is used for these operations, and with such usage comes an equally large amount of discharge into surrounding habitats.

In recent years, disease outbreaks have caused significant impacts to production in these regions (Jung et al., 2020; Kang, Kim, & Kim, 2013). *Edwardsiella tarda* has been a particularly problematic pathogen for the olive flounder industry in Asia, and efforts continue in the battle against this disease (Park, Aoki, & Jung, 2012). In addition to increases in disease-related mortality on farms, olive flounder farms in Asia have also suffered from issues associated with myxozoan parasites, typically of the genus *Kudoa*, which cause post-mortem myoliquefaction of fish tissue (Yokoyama, Whippes, Kent, Mizuno, & Kawakami, 2004). This condition, which is commonly referred to as “jellied meat” or “milky flesh” condition, results in loss of the harvested product due to rapid spoilage. With *Kudoa* species being distributed worldwide, its impacts to a variety of wild and cultured fish species have been well documented (Henning, Hoffman, & Manley, 2013; Langdon, 1991; Whippes et al., 2003). Recently, *Kudoa septempunctata* infections in olive flounder farms of Korea have led to more stringent inspection and quarantine of olive flounder imported to Japan over concerns related to *Kudoa*-induced food-borne illness from consumption of raw olive flounder infected with this parasite (Jae-Min, 2019; Kawai et al., 2012; Yahata et al., 2015). This has given rise to an oversupply and accompanying price declines for Korean olive flounder. As a result of these issues, there is an increased interest in implementation of RAS or semi-RAS systems to help mitigate the risks associated with flow-through farming operations and diseases (Furuta et al., 1998; Honda et al., 1993; Kikuchi, Iwata, & Takeda, 2002).

A multitude of factors have combined to position olive flounder as one of the most promising marine finfish species for developing non-salmonid land-based marine finfish aquaculture in the United States. The following sections will discuss these factors and provide insights into opportunities for expanding production of this species in the United States. Given that the species is already commercially produced in other parts of the world and numerous scientific articles have been published on most of the production biology, nutrition, breeding, and health management of this species, the focus of the discussion will be on the opportunities presented by the species for helping the
United States realize its full land-based marine finfish aquaculture potential. In particular, the species has been identified as a prime candidate for increasing resilience for coastal working waterfront communities in regions where wild-caught flounder fisheries are in decline.

The majority of olive flounder are produced in Asia with fish being reared for both human consumption and stock enhancement purposes. This species is one of the most important marine finfish species produced in Korea and Japan, and as such a plethora of research has been conducted on nearly all aspects of olive flounder production. Therefore, the objectives of the present article are to provide insights on where opportunities may exist for leveraging such vast knowledge of this species into expanded marine finfish aquaculture production in the United States. A brief summary of olive flounder aquaculture is provided for historical context.

Olive flounder aquaculture began in the 1960s in Japan, with researchers at Kindai University's Aquaculture Research Institute (Shirahama 3,153, Nishimuro, Wakayama 649–2,211, Japan) recording the world's first production of farm-raised Japanese (olive) flounder (Harada, Umeda, Murata, Kumai, & Mizuno, 1966). Continued work with this species, including technology transfer to other countries in Asia, notably Korea and China in subsequent decades, allowed for significant expansion of olive flounder aquaculture production (Seikai, 2002). The captive breeding efforts of this species began decades ago, and today producers are reaping the benefits of the extensive domestication efforts with this species. Broodstock fish over 2 years old will spawn volitionally in captivity when conditioned with adequate photothermal regimes, having average spawning water temperatures ranging from 9 to 19°C (Kim & Hur, 1991; Min, 1988; Seikai, Kikuchi, & Fujinami, 2010). Fertilized embryos of good quality are buoyant and can be collected from spawning tanks using surface skimming and egg collectors. After collection, either embryos are stocked into incubation tanks for hatching at densities of 200–400 embryos/L or embryos can be stocked directly into larval rearing tanks at desired rearing densities, which can range from 10 to 80 larvae/L depending on the level of intensity of the larval rearing system. Experimental trials have indicated that higher density larval stocking densities may offer improved production, as long as food supply and water quality conditions are maintained at sufficient levels (Geng et al., 2019). Larval rearing tanks vary in size, configuration, and operation, with rearing techniques adapted for each unique situation. Historically, extensive and semi-intensive larval production techniques, typically corresponding to lower larval stocking densities of 10–20 larvae/L have been applied using larval rearing tanks of 20–80 m³ in size (Seikai et al., 2010), and such techniques are still quite successful. Efforts to prevent losses from disease during the larval rearing period, as well as reduce labor costs associated with flounder seed stock production, have led to the advent of larviculture methods such as the hottoke-shiku, or “stagnant water” method, which aims to establish a more stable bacterial community in the rearing environment (Tomoda, Shigeki, Bullet, & Nakamura, 2011). Intensification efforts have also resulted in improvements of larval rearing production of this species, allowing for increased seedstock production in smaller volume tanks (Geng et al., 2019). The larval rearing of olive flounder typically follows a “standard” marine finfish regime of enriched rotifers (Brachionus sp.) and green water (live algae or algal paste products) in the initial stages, up to ~14 days post hatch (dph), followed by a co-feeding period of 3–5 days with Artemia, beginning with instar stage Artemia on the first 1–2 days of co-feeding, followed by enriched Artemia nauplii. Exclusive feeding of enriched Artemia nauplii continues through metamorphosis up until weaning onto inert diets, which typically occurs ~40 dph. With improvements in microparticulate Artemia replacement diets tailored to marine fish production, it is possible to reduce the amount of Artemia utilization in the larval rearing of olive flounder (Stieglitz et al., unpublished). Given that there is sexually dimorphic size differences in this species, with females growing faster and larger than males (Yamamoto, 1999), it is recommended to keep larval rearing water temperatures between 15 and 19°C, since larvae become males at temperatures ≥20°C (Bai & Lee, 2010). Survival to the fingerling stage (~30 mm TL) is high, on average, compared with other marine finfish species, with survival rates of 40–70% achieved on a regular basis under commercial-scale hatchery production conditions. In regions where olive flounder production is prevalent, the different stages of production (breeding/larval rearing, nursery, and growout) may be segmented across businesses to capitalize on opportunities associated with economies of specialization (Tisdell, 2012). One such area is Jeju Island, Korea, which is widely regarded as the epicenter of global olive flounder production. Here many production facilities may operate in only one stage of the...
production cycle, such as the growout stage, while sourcing seedstock from other entities and thereby retaining an ability to focus on optimization of a single step in the process.

Following the onset of metamorphosis and settlement, size grading becomes crucial to reduce cannibalism and size heterogeneity. Research has shown that maintaining size homogeneity among individuals in tanks, limiting the amount of light in the tank, and providing adequate amount of feed can all help to reduce cannibalism at this stage (Dou, Seikai, & Tsukamoto, 2000). Weaned fingerlings can be reared in nursery tank systems using a variety of tank volumes and dimensions, with optimal nursery and growout water temperatures ranging from 20 to 25°C (Iwata, Kikuchi, Honda, Kiyono, & Kurokura, 1994). Octagonal, square, and raceway types of tanks are commonly used in many olive flounder production facilities, though oval and round tanks are suitable as well but may be less efficient from a floor space utilization standpoint. Nursery-stage fish are typically fed ~3.5–5% bodyweight (BW) per day using commercial pelletized diets (Okorie et al., 2013), with feed amounts (% BW/day) and dietary protein requirements (~60–45%) declining with age up until harvest (Bai & Lee, 2010). A significant amount of aquaculture nutrition research has been conducted with this species, as recently summarized by Hamidoghli et al. (2020). Although historically much of the growout production of this species has relied upon the use of moist pellets and locally available trash fish, principally in Asia, the industry as a whole has been moving toward the use of extruded pellets to help improve the overall production and sustainability of the industry.

The market size for olive flounder is typically 0.8–1.2 kg, which is attainable in 12–18 months depending on water temperature, stocking density, feeding regime, and other factors that can impact growth rates (Kikuchi & Takeda, 2001; Seikai, 2002). Olive flounder are extremely efficient in feed conversion with FCRs between 1.0 and 1.2 (Kikuchi & Takeda, 2001; Seikai et al., 2010). Tank stocking densities for flounder are typically higher than would be used with non-flatfish (i.e., “round fish”) that use the entire water column of the rearing tank. Due to the benthic nature of flounder, densities are typically expressed in terms of kg/m² as opposed to kg/m³, since bottom coverage is the key metric when calculating flatfish production densities. Water depths in nursery and growout tanks range from 30 to 100 cm, with depth increasing as fish grow in size. Stacking densities used in commercial facilities in Korea range from 0.4 kg/m² at the start of the nursery stage (~3.5 cm TL, 0.5 g BW) to 20 kg/m² at the later portion of the growout stage (~42 cm TL, 885 g BW) (Bai & Lee, 2010), though as systems have become more intensified such growout densities have increased over time. The species is also quite adaptable to various salinities, with no adverse impacts to growth in juveniles associated with salinities ranging from 4.4 to 34.0 ppt (Kikuchi & Takeda, 2001).

Although olive flounder production has grown significantly over the past decades in parts of Asia, there are still a number of challenges faced by the industry. Disease is a constant threat, and with the expansion of coastal farms utilizing flow-through production systems comes increased risk of disease outbreaks occurring and spreading rapidly. While the ability to pump and dump seawater when operating along the coast appears to offer cost advantages, such practices come with considerable risks. Flow-through land-based farms are generally unable to effectively optimize the rearing environment to the degree that can be obtained in a RAS facility. Due to the high amount of water exchange necessitated by the high rearing densities in commercial-scale fish culture, flow-through operations with little or no effluent treatment requirements have the potential to cause significant impacts to coastal environments in the areas with close proximity to the farms. This practice also increases the risk of bringing disease into the production facilities, and/or facilities transferring diseases to one another along the coasts. Such issues are not unique to the flounder industry, as similar challenges have faced other land-based coastal production systems such as pond-based shrimp farming throughout the tropics. Additionally, disease issues are not limited to those facilities which use coastal surface waters for flow-through operations, as a number of operators using saline wells in coastal areas have faced disease challenges. Salinity is typically lower in well-water facilities than in those using coastal waters, yet production facilities that have lower salinity appear to face greater challenges associated with scuticociliatosis disease in Asia than facilities with full-strength seawater (Jung et al., 2020). Given the issues associated with using flow-through production systems, there has been a move toward the use of RAS or semi-RAS systems to help overcome such challenges with scuticociliatosis (Takagishi, Yoshinaga, & Ogawa, 2009), as has also been discussed with other diseases noted previously.
Although improvements in water treatment systems address some of the key issues facing the olive flounder aquaculture industry, there remain feed-related issues that contribute to the challenges facing the industry. The continued use of moist pellets, as opposed to formulated extruded diets, in many production facilities in Korea exacerbates existing challenges both from diseases and from environmental impact standpoint. There has been a significant push in recent years to increase adoption of extruded feeds in commercial-scale olive flounder production. Such improvements, when coupled with evidence that a significant amount of the fish meal in olive flounder diets can be replaced with alternative protein sources (Bai & Lee, 2010; Hamidoghli et al., 2020; Kim et al., 2019), reveal a promising future for improved sustainability of the olive flounder aquaculture industry worldwide. Further advancements have been made in continued improvement of seedstock used in the industry through research aimed at advancing genetic selection efforts (Castaño-Sánchez et al., 2010; Kang, Kim, & Lee, 2008; Shao et al., 2015). When combined with the recent mapping of the genome and transcriptome of olive flounder (Shao et al., 2017), such research provides incredible potential for making significant strides in improving the sustainability, profitability, and overall viability of olive flounder aquaculture worldwide.

3 | STATUS OF MARINE RAS AQUACULTURE IN THE UNITED STATES AND REMAINING CHALLENGES

Although development of offshore aquaculture in the United States continues to face a number of challenges, the demand for domestically produced marine finfish shows no signs of abating. In order to meet this demand, farmers and investors have increasingly turned to land-based production as a means to increase marine finfish production in the current regulatory environment. When assessing the pros and cons of different growout systems, the pond- and flow-through-based systems (Methods #1 and #2 from Section 1) are advantageous from an initial capital cost perspective, yet RAS facilities hold a number of advantages when it comes to control and optimization of the growing cycle since it is possible to maintain a stable year-round environment to maximize growth and efficiency of the species being reared. The red drum, *Sciaenops ocellatus*, is a prime example of marine finfish produced commercially in land-based ponds in the United States, though this type of growout production is not well suited for commercial-scale production of many of the other high-value marine finfish species identified as candidates for the United States.

Historically, RAS finfish production in the United States has been aimed at freshwater species, such as tilapia, trout, and barramundi. In general, species of freshwater fish commonly cultured throughout the world are regarded as rather resilient when maintained under low-quality water conditions (Martins et al., 2010), which may be advantageous from an aquaculture perspective. In recent decades, RAS production of marine finfish has grown in popularity, with a number of commercial ventures developed for species including, but not limited to, cobia, *Rachycentron canadum*; yellowtail jacks, *Seriola spp.*; pompano, *Trachinotus carolinus*; tripletail, *Lobotes surinamensis*; seabass, *Dicentrarchus labrax*; and Atlantic salmon, *Salmo salar* growout. The vast majority of these marine finfish RAS developments have shut down over the years, and few, if any, of the ventures have ever been able to generate sustained profitability for any appreciable amount of time, much less been able to generate profits following payback of initial investment costs. The causes for such failures are numerous and unique to each venture, yet when viewed in a generalized sense can be broken down into a handful of common causes: (a) lack of capital at critical stages; (b) inexperience with the species and/or rearing system; (c) lack of consistent availability of high quality seed stock; (d) inadequate systems design and/or operation; (e) poor species and/or site selection; and (f) lack of market research and/or effective marketing strategy. In many cases, operations have failed from a combination of these causes, which in hindsight may appear rather obvious and avoidable.

In order for commercial-scale RAS marine finfish operations in the United States to realize economic viability, the key is to learn from the failures and develop strategies to overcome the hurdles which have historically hampered this sector. Although technological feasibility has been proven with many finfish species cultured in RAS
systems, such operations still face significant financial feasibility challenges when trying to compete with other forms of production (Bostock et al., 2010). Despite the growth in the number of RAS farms worldwide (Badiola, Basurko, Piedrahita, Hundley, & Mendiola, 2018), RAS marine finfish production is still a rather nascent segment of the aquaculture industry and there are few success stories that interested farmers and investors can look to when considering development of new marine RAS finfish ventures. In many cases, the industry is attempting to simply apply technologies and techniques that have proven successful in the freshwater sector to the marine sector. Such practices can commonly be identified by suppliers claiming “turn-key” RAS technology for marine finfish species that have never been cultured in RAS, and one has to wonder how such solutions could be “turn-key” if in fact the technology has never been tested with the selected species. Although applications of freshwater RAS technology can work in some cases for certain aspects of the marine finfish production process, there are numerous cases in which such application has proven to be inadequate and led to overall failure of marine finfish RAS ventures.

In most cases, a better route to developing successful marine finfish RAS operations is to apply engineering designs and production technologies that are best suited for the specific marine finfish species and farming site (Badiola, Mendiola, & Bostock, 2012), while taking into account the overall capital costs associated with such development and the market opportunity for the product. Maintaining an overall goal of de-risking the project to the greatest extent possible is typically the best approach when it comes to any aquaculture project, particularly RAS marine finfish facilities. Such de-risking can come in many forms, yet most center around rather intuitive strategies such as using tried and true marine finfish engineering solutions and production methodologies, capitalizing on well-established market opportunities, and/or selecting finfish species for which genetically optimized seedstock is readily available. De-risking becomes ever more important when taking into account the fact that investor returns on marine finfish aquaculture projects may occur on a longer timeframe than in other animal protein production industries. Such timeframes can be multiplied by two or more when engaging in development of novel species which have never been raised in commercial-scale production settings or when developing species that have no existing market presence. However, the selection of a species with a track record of success in commercial-scale aquaculture settings, albeit perhaps not in RAS, combined with an existing market and product recognition could allow for a relatively low-risk opportunity with potentially reduced timeframes for return on investment. Olive flounder is one such species that fits this description, and development of RAS culture for this species represents one of the most promising opportunities for non-salmonid land-based marine finfish production in the United States.

Olive flounder, when compared with other marine finfish species considered for culture in the United States, holds a number of attractive production advantages. These advantages can be broken down into the following broad categories: production density, growout efficiency in RAS, and market. With relatively shallow water depths used in olive flounder culture systems (30–100 cm deep) combined with high rearing densities, >30 kg/m², and low FCRs (~1.0–1.2) through growout, such production allows for more economically viable RAS facility capital and operation costs. Although economies of scale definitely offer opportunities for increased profitability and operating efficiency of RAS on a commercial scale (Bailey & Vinci, 2020; Engle, Kumar, & van Senten, 2020), such opportunities are sometimes tempered by significant increases in unforeseen challenges. Many recent RAS marine finfish operations opt for developing smaller-scale production units or modules, as opposed to one large facility on a single water treatment loop, as there are production advantages associated with modular RAS culture. Even in the case of large-scale operations, modular RAS construction is still quite prevalent since it allows systems to come online faster in the initial start-up stage while also offering opportunities for reducing operating costs during periods of reduced demand, disease outbreaks, or other situations which may require module shutdown. With RAS marine finfish aquaculture advancements occurring throughout the world, and lessons being learned from the multitude of failed operations over the years, it appears that economically viable commercial-scale operations may soon be a reality in the United States.

Additional factors support the notion that this is a favorable time for development of marine finfish aquaculture operations in the United States, and specifically in the case of olive flounder land-based RAS operations. High startup capital costs associated with marine RAS operations have historically been above that which could be justified with resulting production tonnage and price per pound of the final product for nearly all marine finfish species. However,
with improved production efficiency of modern-day advanced RAS systems, reduced capital costs over time per ton of fish produced in marine RAS, and an increased price per pound paid by consumers for premium marine finfish, particularly flatfish species, it appears that conditions have reached a point where RAS marine finfish production of high-value species can be economically viable in the current global climate (Figure 1). Analysis of different types of finfish production in the United States across various species and growout systems notes that one of the keys to RAS being profitable is to increase the tonnage (volume) of fish produced per capital investment dollar (Engle et al., 2020). RAS-produced olive flounder offers an opportunity to capitalize on this relationship, whereby the species attains premium market prices (Bai & Lee, 2010) compared with other marine finfish species and it is able to be produced at significantly higher volumes per dollar of RAS investment capital. Overall the global aquaculture industry is experiencing positive trends in production efficiencies due to advances in genetic improvement, nutrition, engineering, and operational/automation (i.e., reduced labor costs per ton of fish produced). Coupled with socioeconomic factors such as population growth, increasing per capita seafood consumption, rising consumer willingness to pay for seafood, and forecasts indicating farm-raised fish prices are expected to outpace those attained for wild-caught products (FAO, 2020), marine RAS is becoming a viable option for the United States.

### 4 OPPORTUNITY FOR AQUACULTURE TO INCREASE RESILIENCY IN WORKING WATERFRONTS OF THE UNITED STATES

Globally, coastal communities remain some of the most densely inhabited areas on earth. In the United States, nearly 40% of the human population lives in coastal areas (NOAA & U.S. Census Bureau, 2013), with working waterfronts experiencing the most severe impacts as sea level rise accelerates, and coastal erosion, storms, and flooding become more frequent and intense.

#### Figure 1

Increased efficiency (RAS capital costs per ton of fish produced) of marine RAS systems over time compared with higher flounder prices over time. A representative figure illustrating that a combination of factors, notably the market for the species and improved production efficiency, result in opportunity for economically viable RAS production of flounder. The trend of increased economic efficiency of RAS production over time is represented theoretically by a decreasing cost per ton of fish produced over time and is based on technological advancements and improved efficiencies realized across numerous aspects of RAS marine finfish production over the past few decades. The intersection point of the lines is theoretical and represents an approximated timeframe of when economically viable production of flounder in marine RAS could be possible due to factors discussed.
communities representing key areas of economic activity within coastal zones. However, as human population continues to grow, population centers are becoming increasingly decoupled from traditional food production areas such as cropland and pasture areas (Kummu et al., 2016). In coastal communities, where historically there has been a greater reliance on locally available food sources from the sea compared with other communities, static or in many cases declining wild fisheries have forced many communities to look elsewhere for seafood while leaving working waterfronts idle. The decoupling of U.S. fishers and domestic consumers is clearly evident when examining imports and exports of U.S. seafood. The United States imports over 90% of the seafood consumed in the country, of which over half is farm-raised, leading to a seafood trade deficit of $16.8 billion dollars in 2017 (NOAA - NMFS, 2020). These importation and deficit figures are expected to rise in coming years unless domestic seafood production is increased significantly. Although per capita seafood consumption has remained relatively static in the United States at ~15–16 lb per person per year, when factoring in the growing U.S. population, the overall U.S. consumption of seafood is expected to increase (NOAA - NMFS, 2020; Shamshak, Anderson, Asche, Garlock, & Love, 2019). Also, revised seafood consumption guidelines for Americans from the U.S. Department of Agriculture (USDA) and the U.S. Department of Health and Human Services (USDHHS) recommending increased weekly seafood consumption particularly in women who are pregnant or may become pregnant will potentially lead to increased U.S. per capita seafood consumption in coming years (USDHHS & USDA, 2015). Such demand theoretically results in increased economic opportunities for seafood producers in working waterfront communities, yet wild fisheries tonnage landed in the United States has been declining (NOAA - NMFS, 2020). Overfishing, habitat loss, climate change, shifting fisheries, regulatory restrictions, and pollution of coastal waters are all issues contributing to a rather sobering outlook for global fisheries, yet sustainable aquaculture has emerged to play a critical role in meeting the ever-increasing global demand for seafood.

Already >50% of the seafood consumed by Americans, on average, is farm-raised, yet the marine fish farming industry in the United States is virtually nonexistent. The coastal regions of the United States represent prime candidate areas for development of marine fish aquaculture, particularly in areas where working waterfront communities already exist and there is urgent need for increased economic resiliency. Additionally, per-capita consumption in coastal areas is higher than in other regions of the United States (Love et al., 2020), providing opportunities for increased “farm-to-table” consumption of seafood in such regions. However, ventures attempting to commercially culture fish in nearshore coastal or offshore waters are faced with a myriad of onerous, and sometimes impossible, hoops to jump through from a regulatory, permitting, and social acceptance standpoint. Furthermore, culturing fish in these types of open systems exposes farmers and investors to higher levels of risk compared to operations that occur in land-based settings. These factors, along with the high costs of production typically associated with starting an aquaculture venture from scratch, are largely responsible for stymieing the flow of capital into open-ocean marine fish aquaculture ventures in the United States. Extractive species culture, such as shellfish and seaweed aquaculture, have emerged in some regions of the United States as promising alternatives for working waterfront communities that historically relied upon wild catches. Despite the increases in domestic extractive species production, such operations do not satisfy the growing demand for marine finfish in the United States that is currently met by foreign imports.

Many of the hurdles associated with development of open-ocean aquaculture in the United States are ameliorated in land-based marine RAS finfish aquaculture development. Aquaculture in general is well suited to being integrated into working waterfront communities, as much of the infrastructure and skilled labor is usually present. Access to saline water used in marine RAS is also typically easier in coastal areas compared to sites further inland. However, the adoption of this type of aquaculture production technology for marine species has been slow. In many communities, finfish aquaculture still faces significant social license challenges due in part to decades of misinformation campaigns from opponents of the industry (Froehlich, Gentry, Rust, Grimm, & Halpern, 2017). Incorporating modular land-based RAS finfish facilities in working waterfronts of the United States may offer opportunities to not only provide much-needed economic alternatives to fishers, but also allow these communities to have hands-on experience with environmentally sustainable marine finfish farming. Such community-level experience and
improved communication has been shown to be instrumental in helping overcome many of the social license issues facing the aquaculture industry. One of the keys to realizing success with such operations is selection of a marine finfish species that is economically viable to be cultured in such modular RAS facilities. Olive flounder is one such species that has unique attributes from both biological and market perspectives to succeed in modular RAS facilities incorporated into working water fronts, particularly in areas of the country where wild flounder catches have declined dramatically over past years such as along the East Coast of the United States (Figure 2). These declines elicit a sense that wild-caught fisheries may no longer be able to sustain the livelihoods of working water fronts, yet this offers an opportunity for technological innovation to respond as has occurred in the seafood industry many other times during other periods of scarcity-induced innovation (Asche & Smith, 2018). Development of land-based marine finfish RAS operations in working water fronts may be one of the key innovations that offer an opportunity for increased resilience in these vital coastal communities.

5 | U.S.-BASED EFFORTS TO DEVELOP FLOUNDER AQUACULTURE

Flounder aquaculture in the United States is not a new endeavor, though currently there is no economically viable commercial-scale culture of flatfish in the country. The lack of such operations is rather surprising, given the success with commercial-scale flatfish culture in other parts of the world. Domestic landings of wild flounder species, as well as low-cost imports of frozen wild and farm-raised flounder species, have comprised the majority of the flounder supply in the United States. With decreased wild capture in many parts of the United States, particularly in regions with high demand such as the East Coast/Atlantic States region (Figure 2), there has been significant interest in development of flounder aquaculture. Much progress has been made in advancement of aquaculture techniques for domestic flounder species such as summer flounder, Paralichthys dentatus; winter flounder, Pseudopleuronectes americanus; and southern flounder, Paralichthys lethostigma over the past decades (Benetti, Grabe, et al., 2001; Benetti, Leingang, et al., 2001; Bengtson & Nardi, 2010; Daniels & Watanabe, 2010; Fairchild, 2010; Smith et al., 1999). However, a number of challenges remain in realizing commercial-scale closed-cycle production with any of the domestic species.

![Figure 2](image_url) Commercial landings of flatfish species from the East Coast regions of the United States over time. Data from NOAA Landings Database (years: 1950–2019)
Olive flounder has a number of attributes, many of which have been discussed in prior sections, which position it as a prime candidate species for land-based RAS marine finfish culture in the United States. With a more rapid growth rate compared with other cultured flatfish species (Table 1), well-established production techniques, and a high-value market, the species offers incredible potential. From a marketing standpoint, the species can be marketed as either “hirame,” which is the more common product name in Asian markets, or as “flounder” in markets of the United States where “flounder” is a well-known and sought-after product. Olive flounder aquaculture overcomes many of the issues associated with trying to market low-value or relatively unknown marine fish species. For any business to succeed in the aquaculture industry, the product must have a strong market, relatively high margins between production and farm-gate costs, and have a competitive advantage to provide resilience in the face of intense competition from other domestic and foreign seafood products. There is potential for farm-raised olive flounder produced in the United States to meet all of these requirements under proper culture and marketing conditions.

Researchers at the University of Miami (UM) – Aquaculture Program have been culturing olive flounder at the UM Experimental Hatchery (UMEH) facility since 2015. Over the past years, much progress has been made in refining production techniques and adapting the well-established production methodologies used elsewhere in the world to the specific conditions in land-based production systems in South Florida. Environmental control using water temperature manipulations of the spawning cycle has allowed researchers at UMEH to spawn the fish on a year-round basis and to control the cycle according to production needs. The broodstock fish spawn volitionally in water temperatures of 13–17°C at the UMEH facility, and methodologies for management of temperature cycles to induce volitional spawning are similar to those reported by Benetti (1997) for the speckled flounder, Paralichthys woolmani. Breeding fish are fed a premium diet of thawed sardines and squid with regular addition of vitamin and mineral supplements, as detailed in Stieglitz et al. (2017) for other species of marine fish at UMEH, to maintain peak spawning performance and production of high-quality eggs. Multiple generations of fish have been reared to market size, and beyond, over this time at UMEH. Interestingly, olive flounder production at UMEH has encountered virtually none of the pseudo-albinism pigment abnormalities on the ocular side of fish as have been reported in literature for other flatfish species, including olive flounder under certain conditions (Seikai & Matsumoto, 1994; Venizelos & Benetti, 1999). Pigment abnormalities on the ocular side of the fish can significantly decrease the market value of harvested product, and the lack of such abnormalities is yet another positive trait for the species currently being

| Species of flatfish (farm-raised for human consumption) | Growout time (months) | Average market size (kg whole harvested fish) | Relative market price |
|--------------------------------------------------------|-----------------------|-----------------------------------------------|----------------------|
| Olive flounder, Paralichthys olivaceus                  | 12–14                 | 0.8–1.5 kg                                    | $$                   |
| Atlantic halibut, Hippoglossus hippoglossus             | 40–52                 | 3–7 kg                                        | $$$                  |
| Turbot, Psetta maxima/Scophthalmus maximus              | 18–24                 | 0.5–1.2 kg                                    | $$                   |
| Sole, Solea spp.                                        | 16–18                 | 0.35 kg                                       | $$$$$                |
| Chilean flounder, Paralichthys adspersus               | 20–25                 | 0.25–0.55 kg                                  | $$                   |
| Summer flounder, Paralichthys dentatus                 | 20                    | 0.45 kg                                       | $$                   |
| Southern flounder, Paralichthys lethostigma            | 16                    | 0.5 kg                                        | $$                   |
| Winter flounder, Pseudopleuronectes americanus         | 24–36                 | 0.45–1.0 kg                                   | $$                   |

Source: 1: University of Miami Experimental Hatchery (unpublished); 2: Seikai et al. (2010); 3: Holmyard (2015); 4: Lei and Liu (2010); 5: Person-Le Ruyet (2010); 6: FAO (2014); 7: Silva (2010); 8: Carroll, Watanabe, and Losordo (2005); 9: Benetti, Leingang, et al. (2001); 10: Fairchild (2010).
Olive flounder, Paralichthys olivaceus, culinary preparation (photo: University of Miami Aquaculture)
is beyond what is typically termed “commercially ready.” The source stock currently cultured at the University of Miami has already gone through multiple generations of selective breeding in overseas aquaculture programs to overcome many of the challenges that have traditionally held back commercial culture of other flounder species in the United States, such as the southern, winter, and summer flounders. Olive flounder is the fastest growing of all of these species, reaching a market size of 1 kg in 1 year or less under optimal conditions, and rearing methods at the University of Miami are continuing to be refined to further improve and de-risk the entire production process. As the land-based RAS marine finfish industry looks to expand in the United States, olive flounder is a prime candidate species to lead the way toward economically viable, environmentally sustainable, and socially responsible aquaculture development.

From a regulatory perspective, there are no issues with raising this species of flounder in land-based RAS facilities, as long as the rearing system and water discharge are designed in ways that adhere to local, state, and federal regulations. The ability for commercial-scale quantities of juveniles to be shipped from the existing seedstock production facility in the United States at the University of Miami allows prospective farmers to bypass the need to construct broodstock, hatchery, and nursery facilities and thereby focus entirely on the commercial growout of the product. This means cost-effective modular facilities could be set up in existing, yet un- or under-utilized, working waterfront spaces along coastal regions of the United States, thereby helping accelerate environmentally sustainable aquaculture while creating jobs, providing income diversification opportunities, and increasing community resilience.

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