The status of California halibut, *Paralichthys californicus*, as a technologically feasible species for marine U.S. aquaculture

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**Abstract**

California halibut (CH; *Paralichthys californicus*) is a highly valued species that supports a commercial and recreational fishery along the Pacific coast of the United States. This species is considered a promising aquaculture candidate in California, with interest for both food production and stock replenishment. Culture of CH has been done on a small scale, showing that it is technologically feasible to rear this species commercially. Broodstock maturation and egg production can be accomplished without hormone therapy. Survival from egg to juvenile (~50 dph) can be as high as 30%. Juvenile growout to market size has been done on a limited basis, and it takes 3 years to reach a market size of 1 kg. There is a live market for CH in California and it is currently being supplemented by the importation of *Paralichthys olivaceus*. The known disease agents affecting CH are ectoparasites (i.e., *Trichodina sp*), endoparasites (i.e., *Anisakis sp*), and bacterial agents (i.e., *Pseudomonas sp*). While culture of this species is technologically feasible, research still needs to be done in certain areas in order to realize commercial readiness. These areas include: nutrition, selective breeding, development of all female populations; improved pigmentation; and developing methods for disease prevention and control.

**KEYWORDS**

commercial feasibility, flatfish culture, marine finfish, *Paralichthys*
INTRODUCTION

Flatfish have been commercially produced in Asian and European countries for several decades, with species of interest being Japanese flounder (*Paralichthys olivaceus*), turbot (*Scophthalmus maximus*), Atlantic halibut (*Hippoglossus hippoglossus*), and sole (*Solea solea*) (Bronley, Sykes, & Howell, 1986; Daniels & Watanabe, 2010; Ikenoue & Kafuku, 1992; Seikai, 2002). Successful flatfish culture in the United States has been demonstrated with multiple *Paralichthys* spp., including summer flounder (*Paralichthys dentatus*), southern flounder (*Paralichthys lethostigma*), and California halibut (CH; *Paralichthys californicus*) (Benetti et al., 2001; Conklin et al., 2003; Daniels & Watanabe, 2010; Watanabe & Feeley, 2003).

CH is the largest of 18 species recognized in the genus *Paralichthys*, reaching a maximum size of 33 kg and living up to 30 years (Kramer, Sunada, & Wertz, 2001). They range in distribution from Washington State to Baja California, Mexico (Kramer et al., 2001). Adults are mostly found along the open coast on sand substrates. Spawning occurs offshore and settlement occurs in shallow coastal areas before most of the young juveniles migrate into embayments, which are used as nursery areas. This life history information is useful in guiding aquaculture practices because it suggests that eggs and larvae most likely require stable temperature and salinity conditions, while settled juveniles are more euryhaline and temperature tolerant.

CH is a popular flatfish that supports both a commercial and recreational fishery along the Pacific coast of the United States (Allen, 1990; Kramer et al., 2001). The total landings of CH in California in 2019 were 324 m.t., which equated to a value of $3.3 million (CDFW 2019). Of that $3.3 million, $1.3 million was landed in southern California (Santa Barbara, Los Angeles, and San Diego). Culture for this species began on an experimental level in the 1980’s for the purposes of stock replenishment. Since that time, hatchery research has been done in several locations in California and Baja California, Mexico (Caddell, Gadomshi, & Abbot, 1990; Conklin et al., 2003; Vizcaino-Ochoa, Lazo, Baron-Sevilla, & Drawbridge, 2010). Currently in the United States, Hubbs-SeaWorld Research Institute (HSWRI), San Diego, CA, is the only research team culturing CH because there is renewed interest in stock enhancement. Developments in commercial culture of CH have been constrained by a lack of information on broodstock selection, feed formulations for all life stages, and optimization of juvenile growth (HSWRI personal communication, Conklin et al., 2003, Merino, Piedrahita, & Conklin, 2007a, Merino, Piedrahita, & Conklin, 2009, Vizcaino-Ochoa et al., 2010). Here we review what we know about the culture of the species while also identifying areas were more research is needed.

CULTURE TECHNIQUES

2.1 Broodstock (systems, collection, husbandry, spawning)

CH brood fish are typically collected as adults by hook and line in nearshore waters. As a visual ambush predator, transitioning CH to feed in captivity can be challenging. We often transition newly collected fish onto frozen squid and sardines using live baits or frozen fish towed on fishing line through the water to simulate swimming. Once acclimated, we feed our broodstock 3–5 times per week at 1–3% bodyweight with each feeding. Broodstock holding densities typically range from 1.5 to 4.0 kg/m³ and tank volumes range from 10 to 150 m³ (HSWRI unpublished data, Caddell et al., 1990; Conklin et al., 2003). The male to female ratio used is typically 1:1 and is similar to other flatfish species (HSWRI unpublished data, Caddell et al., 1990, Watanabe, Elli, Ellis, & Feeley, 1998, Benetti et al., 2001, Conklin et al., 2003, Watanabe, Woolridge, & Daniels, 2006).

CH is a batch spawner that spawns throughout the year in the wild, with peaks in winter and spring (Kramer et al., 2001). The spawning interval is reported to be 1.3–2.7 days in the wild (Barnes & Starr, 2018). Parentage analyzes have not been done for this species to determine spawning intervals or batch fecundity parameters in a captive setting. In our experience with captive CH, females release eggs when water temperatures are between 15 and...
21°C. Volitional spawning has been successful with and without hormones (Caddell et al., 1990). The adults will spawn under controlled lighting and temperature, as well as under ambient conditions, much like other *Paralichthys* species (HSWRI unpublished data, Caddell et al., 1990, Watanabe et al., 1998, Smith et al., 1999, Boccanfuso, Aristizabal Abud, & Berrueta, 2019). In recent years at HSWRI, our egg production has varied from 66 to 169 million eggs per year (Table 1). The difference in egg production was a result of different tank dimensions and associated volumes, different numbers and individuals of wild breeders, and the addition of temperature control to one tank in 2019. With temperature control, we were able to maintain a constant 17–18°C temperature during the peak spawning season, which allowed for consistent and predictable spawning from April through June (Figure 1). Caddell et al. (1990) also reported good success with CH under controlled conditions and demonstrated consistent egg production over three consecutive years. They reported 5–13 natural spawn events per year with averages of 325,000–455,000 eggs per spawn. At HSWRI, we recently recorded 57–116 spawns across three years with

| Variable                  | 2014        | 2015        | 2019        |
|---------------------------|-------------|-------------|-------------|
| Number of spawns          | 57          | 85          | 116         |
| Number of females         | 3           | 6           | 5           |
| Female biomass (kg)       | 41          | 53          | 37          |
| Total eggs produced (kg)  | 66,136,961  | 125,165,125 | 169,792,465 |
| Batch fecundity (eggs/spawn) | 1,160,297  | 1,472,530   | 1,463,728   |
| Percent viability (mean ± SD) | 33.1 ± 28.8 | 47.3 ± 31.5 | 61.2 ± 30.1 |
| Percent hatch (mean ± SD) | 61.1 ± 16.8 | 74.5 ± 17.5 | 67.6 ± 15.3 |

**Figure 1** Spawning profiles of California halibut (*Paralichthys californicus*) in 2019. The black bars show daily egg production (x1,000) on the primary y-axis and the solid grey line describes daily water temperatures (C) on the secondary y-axis.
averages of 1.16–1.47 million eggs per spawn, which is triple what Caddell et al. (1990) reported (Table 1). This difference may have been a function of female size or the number of females spawning per evening. According to Barnes and Starr (2018), mean batch fecundity for CH in central California is 597,445 (± 318,419) eggs per spawn, suggesting that our fish were either more fecund or more in synch with spawning. Parentage analyzes would be useful in determining this precisely. Our egg viability ranged from 33 to 60%, which is generally low for the pelagic marine species (California yellowtail; Seriola dorsalis and white seabass; Atractoscion nobilis) we work with (Table 1). However, these viability rates are similar to southern and summer flounder, which are documented to have rates as high as 33% and 41% respectively (Watanabe et al., 2006; Watanabe, Carroll, & Daniel, 2001). Furuita, Tanaka, Yamamoto, Shiraishi, and Takeuchi (2001) reported viability rates for P. olivaceus between 60 and 90%, which suggests that there is potential for improving viability of CH spawns. The mean yearly hatch rates for CH at HSWRI range from 60 to 70% (Table 1). Other species such as P. orbignyanus, P. dentatus, and P. olivaceus have reported hatch rates ranging from 64 to 100% (Boccanfuso et al., 2019; Furuita, Tanaka, Yamamoto, Suzuki, & Takeuchi, 2002; Furuita, Yamamoto, Shima, Suzuki, & Takeuchi, 2003; Watanabe & Feeley, 2003). Overall, CH is a highly fecund species and well suited for the culture environment; however, there are research areas that need to be explored to help optimize egg production and egg quality. Two main areas of research include, broodstock nutrition and selective breeding, which have been done extensively for P. olivaceus in both Japan and South Korea, and can be directly applied to CH.

2.2 Larval culture (systems, husbandry, performance)

CH eggs hatch in 36–48 hr after fertilization at 18–20°C (Conklin et al., 2003). Newly hatched larvae range in size from 2.1–2.3 mm and within 1–2 days post hatch (dph) the mouth opens and the eyes become pigmented (Conklin et al., 2003; Gisbert, Piedrahita, & Conklin, 2004). The feeding regime used at HSWRI is described in Figure 2. We feed enriched rotifers from 3 to 17 dph; enriched second instar Artemia from 14 to 40 dph; and a formulated microdiet (Otohime) starting at 25 dph. The halibut are fully weaned onto the microdiet by 40 dph.

An optimized, custom enrichment regime for both rotifers and Artemia has yet to be developed for CH. Researchers have adapted commercial enrichments for rotifers including Rotimac, Isochrysis algae paste, Nannochloropsis algae paste, Algamac 3050, and OriCulture (HSWRI personal communication, Gadomski & Caddell, 1991, Conklin et al., 2003). Similarly, Artemia have been enriched with Easy Selco, S.presso, and Algamac 3050 (HSWRI personal communication, Conklin et al., 2003, Gisbert et al., 2004). The nutritional profile for the live prey being offered to larval flatfish is a critical factor to ensure not only growth and survival, but also proper pigmentation. Improper pigmentation, either albinism or ambicoloration, is a common problem in hatcheries rearing flatfish (Venizelos & Benetti, 1999, Bolkar & Hill, 2000, Ivankov, Ivankova, & Vinnikov, 2008, Vizcaino-Ochoa 2010). Among nutritional factors, pigmentation can be influenced by the dietary levels of vitamin A, docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) (Dedi, Takeuchi, Seikai, & Watanabe, 1995; Dhert, Lavens, Dehasque, & Sorgeloos, 1994; Furuita et al., 2001; Izquierdo, Arakawa, Takeuchi, Haroun, & Watanabe, 1992; Kanazawa, 1993;
Rainuzzo, Reitan, Jorgensen, & Olsen, 1994; Ronnestad, Helland, & Lie, 1998; Ronnestad, Hemre, Finn, & Lie, 1998; Sargent et al., 1999; Takeuchi et al., 1995; Watanabe, 1993). These dietary requirements have not yet been determined for CH larvae, highlighting this as an essential area of research in order to improve larval and juvenile quality.

The culture environment (e.g., light level and duration, turbidity) also has an impact on growth, survival, and quality for flatfish species. Light intensity has been shown to influence both growth and pigmentation in summer and southern flounder. Researchers have reported preferred light intensity ranges from 50 to 2,000 lx for summer flounder and 50–100 lx for southern flounder (Denson & Smith, 1997; Watanabe & Feeley, 2003). Fuentes-Quesada and Lazo (2018) describe light intensity of 72 lx for rearing CH. We have used a range of light intensity from 150 to 3,000 lx at the water surface with no difference in survival or growth; unfortunately, there are no experimental data on the impact of light intensity on pigmentation for CH. Photoperiod is another factor that is known to influence growth rates in marine finfish and typically increasing growth rates are seen due to an increase in day length (Boeuf & Le Bail, 1999; Villamizar et al., 2011). We have used both 24 and 18 hr light with good success. Other researchers have used 14, 18, and 24 hr light with other Paralichthys species (Fuentes-Quesada & Lazo, 2018; Moustakas, Watanabe, & Copeland, 2004). Finally, like other marine fishes, turbidity is used in flatfish culture to provide contrast, usually by the addition of algal or inorganic particles in combination with a specific tank color (Shaw, Pankhurst, & Battaglene, 2006; Stuart & Drawbridge, 2011; Utne-Palm, 2004). We apply a greenwater technique during the first 14 days of culture using Nannochloropsis paste (Reed Mariculture) at a density of about 250,000 cells per ml.

Larval systems and juvenile rearing tanks for CH have yet to be standardized because production is still mostly experimental. Larval tank volumes have ranged from 60–5,000 L and have been operated as both flow through and reuse. This species appears to be adaptable to most culture environments but larval system optimization, as well as proper larval nutrition, is necessary to advance the species commercially.

2.3 Juvenile culture (systems, husbandry, performance)

Settlement for CH occurs close to the completion of eye migration, starting around 27 dph and ending near 35 dph. Prior to settlement, flatfish are usually transferred to juvenile culture tanks, which are typically shallow, square, rectangular, or circular tanks (Lmsland et al., 2007; Labatut & Olivares, 2004; Merino, Piedrahita, & Conklin, 2007b). However, raceways have become popular tanks for flatfish culture primarily because of the simplicity of construction, ease of harvesting and husbandry, and the high surface area per volume of water needed (Klokseth & Oiestad, 1999; Labatut & Olivares, 2004; Merino et al., 2007a; Watten & Johnson, 1990). Raceways have been used successfully to culture CH (Merino et al., 2007a, 2007b, 2009; Oiestad, 1999). More specifically, the use of a shallow raceway allows for the maximization of the bottom area where the fish are able use 200–300% of the available tank space by stacking on top of each other, as well as creating consistent current pattern throughout the tank (Lmsland et al., 2007; Labatut & Olivares, 2004). Merino et al. (2007a, 2007b, 2009) and Merino, Piedrahita, and Conklin (2007c) provide detailed information on raceway system design, stocking density, and defining water quality parameters in order to optimize CH juvenile growth and survival. We have used both circular flat bottom tanks and raceways to produce significant numbers of juveniles. For example, in two recent production runs, we reared CH starting from eggs in a circular, flat-bottom, fiberglass larval tank (5,300 L) up to pre-settlement at 26 dph. Then we transferred the larvae to two 1,000 L circular flat-bottom tanks for settlement, and at 100 dph, we used shallow water raceways for grow out. Overall, this process produced over 200,000 juveniles with survival rates from egg to 55 dph juvenile (0.017 g) of 14 and 28%.

2.4 Growout (systems, husbandry, performance)

There are limited data to inform growers about the growout potential of CH. We have grown CH for as long as 4.6 years and achieved a maximum average size of 1.6 kg (± 0.4 kg) in this cohort. However, this growout was
conducted in a flow through raceway under ambient conditions without optimizing diet or environmental parameters. Among the fish we subsampled, one fish grew to 2.5 kg in 3.7 years, which illustrates the growth potential of the species. Sexual dimorphic growth in *Paralichthys* spp. is well known, with the females having faster growth than the males (Audet & Tremblay, 2011; Fitzhugh, Crowder, & Monaghan Jr., 1996; Yamamoto, 1999). As recently as 2019, HSWRI was able to assess the sex ratio of three different production runs and found a high percentage of males (75–95%). We believe that this skewed sex ratio is due to the culture environment (i.e., tank color, rearing temperatures) during the larval and early juvenile culture period (Madon, 2002; Mankiewicz et al., 2013). Figure 3 shows the growth profiles for wild male and female CH based on fisheries age and growth studies compared with fish cultured at HSWRI (McNair et al., 2001). In the wild, female CH reaches a 1 kg size in just over 3 years. In contrast, other species of *Paralichthys* can reach 1 kg in size in 14–16 months (Watanabe, Alam, Carroll, Daniels, & Hinshaw, 2019). The slow growth to market size coupled with differences in growth between the males and females makes research to improve juvenile growth important for commercialization. Key areas of research to improve the growth of CH would include the development of commercial diets that promote good growth; improved understanding of optimum rearing conditions like water temperature in order to maximize growth, especially in water reuse systems; methods to develop all female populations; and selective breeding. The goal would be to match or exceed the growth rates seen in *P. olivaceus* and achieve a market size in 1–2 years.

3 | DISEASE AND PREVENTION

CH is prone to ectoparasites that include ciliates such as *Trichodina* sp., *Uronema* sp.; flagellates such as *Ichthyobodo* sp.; and sea lice copepods; most of which are readily treatable at low to moderate infestations. *Cryptocaryon* sp. are ciliated protozoans that have both free-swimming and encysted forms making them more difficult to treat. *Cryptocaryon* sp. have caused significant broodstock losses in certain *Paralichthys* spp. regardless of infestation load (Rigos, Pavlidis, & Divanach, 2001). Endoparasites include visceral nematodes; specifically *Anisakis* sp., the larvae of...
which can invade the muscle and coelom of several fish species (Aibinu, Smooker, & Lopata, 2019). Humans who consuming raw fish infected with *Anisakis* larvae can develop zoonotic gastrointestinal illness (Mladineo & Poljak, 2014). Bacterial agents include *Tenacibaculum* sp., *Pseudomonas* sp., and members of the family *Vibrionaceae*, such as *Photobacterium damselae* ssp. *damsela*. *P. damselae* has caused mass mortality in a variety of marine fishes, both wild and cultured, and it can cause human infections as well (Labella et al., 2006; Rivas, Lemos, & Osorio, 2013).

### 4 | MARKET CONSIDERATIONS

Currently, there is no commercial production of cultured CH, so the market characteristics are not defined. The wild CH fishery and landings in California provide some information regarding market potential but cultured fish will undoubtedly be consistently smaller in size, more consistent in size, and more readily available seasonally than wild CH. In 2019, the total landings in California were approximately 324 m.t. valued at $3.9 million, with about $1.3 million from southern California (approximately $12/kg for head-on gutted fish; California Department of Fish and Wildlife, 2019). There is a live fish market for flatfish in California, which is made up of wild-caught CH and imported cultured *P. olivaceus* (Hirame). The volume of this live fish market is not known and import records are not readily available for live fish coming into California. For maximum value, cultured CH would supplement the Hirame market, which has an estimated value at $22/kg for 2–4 kg live fish (Personal Communication David Rudie). Currently the Hirame market has a minimum size of 1.5 kg, so smaller size fish would require additional marketing to determine the feasibility. Overall, there is good market potential for CH if research needs are addressed to improve growth rates so that CH can be integrated into the existing Hirame market. Local production should see economic benefits from reduced transport costs for live fish (e.g., being shipped in from Korea). This approach also reduces ecological risks associated with importation of non-native species that are live. The size of the Hirame market in the USA is also not known.

### 5 | CONCLUSIONS

CH is a promising aquaculture species in California and has been identified as a good candidate for farming since the 1980's. Initial interest in culturing CH has stemmed from recreational fishers interested in stock replenishment, but this could serve as a springboard for food fish production as has happened for many other species of farmed fish. The aquaculture of this species is technologically feasible based on the amount of information known about CH and the successful commercialization of other *Paralichthys* species. This species is not yet commercially viable because of its slow growth to a market size, which makes the cost of production too high. Further research and development is needed before this species can be commercialized in the United States.

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**CONFLICT OF INTEREST**

The authors declare no conflicts of interest.

**AUTHOR CONTRIBUTIONS**

K.S.: Manuscript preparation and revision, submission of the manuscript. C.S.: Manuscript preparation and revision. M.D.: Manuscript preparation and revision.
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