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High-density nursery culture of recently-settled blue king crabs (*Paralithodes platypus*): Comparisons to red king crabs (*Paralithodes camtschaticus*)

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ABSTRACT

Stock enhancement through the release of cultured juveniles has been suggested as a possible recovery tool for depleted red (*Paralithodes camtschaticus*) and blue (*Paralithodes platypus*) king crab populations in Alaska, USA. Considerable progress has been made in the past decade in red king crab culture technology, but similar technologies are less developed for blue king crabs. As part of a stock enhancement feasibility study, hatchery-raised blue king crab juveniles were cultured from larvae of ovigerous females collected off Saint Matthew Island, Alaska. Juvenile instars were then cultured in indoor nursery containers for 42 days at stocking densities of 500, 1000, 2000, 4000, and 6000 crabs m^{-2} starting at metamorphosis to the first instar stage (C1). At day 42, survival was above 90% at all the densities, but had a slightly decreasing trend that ranged from 96% at 500 crabs m^{-2} to 90% at 6000 crabs m^{-2}. The numbers of crabs cannibalized increased with density, but the overall increase in crab biomass offset the negative effects of cannibalism. Survival rates and biomass production for the first 42 days post-settlement is much higher for blue king crabs compared to red king crabs reared under identical conditions. The low rate of cannibalism implies that blue king crabs are well suited for large-scale hatchery culture. Our results suggest that these two closely related crab species can be reared at different stocking densities immediately flowing settlement and that high densities will maximize hatchery efficiency for blue king crabs. Future studies should investigate longer term nursery culture, beyond 42 days, to refine protocols for extended blue king crab rearing. Improving nursery techniques will boost the productivity and financial viability of a large-scale stock enhancement program.

1. Introduction

Stock enhancement through the release of cultured juveniles has been suggested as a possible recovery tool for depleted red (*Paralithodes camtschaticus*) and blue (*Paralithodes platypus*) king crab populations in Alaska, USA, because of their high commercial value and the fact that recruitment limitation has been proposed to explain their lack of recovery in the absence of fishing (Blau, 1986). Much progress has been made over the past decade in the development of red king crab large-scale culture technology (Copeman et al., 2012; Daly et al., 2009, 2012; Kovatcheva et al., 2006; Stevens, 2006a; Swingle et al., 2013). Survival rates of 50% from stocking recently-hatched larvae to the post-larval, glaucothoe stage and 20% from stocking to the first juvenile instar stage are frequently achieved on a large-scale for red king crabs (Swingle et al., 2013) and compare favorably to large-scale hatchery rearing of other crab species (e.g., Hamasaki et al., 2011; Kogane et al., 2007; Zmora et al., 2005). Yet similar technologies for blue king crabs are less developed (but see Stevens et al., 2008), mainly because of logistical difficulty in broodstock acquisition and larval mortality attributed to sensitivity to hatchery conditions.

Blue king crabs occur in isolated populations throughout the North Pacific including waters off Alaska, USA, Japan, and Russia and have a complex life cycle including four planktonic larval stages, a semi-benthic post-larval stage, and benthic juvenile and adult stages. Blue king crabs reproduce biannually: females mate in spring/summer and brood their embryos for approximately 14 months (Jensen and Armstrong, 1989; Somerton and Macintosh, 1985). Larvae (zoeae) spend several months in the water column feeding on phytoplankton and zooplankton. After molting through four stages, zoeae metamorphose into the semi-benthic, non-feeding post-larval (glaucothoe) stage where they settle in complex benthic habitats and molt into the first juvenile crab stage (Tapella et al., 2009). Early benthic phase juveniles (approximately age 0–2 years) have a strong affinity for habitats with complex physical structures (Armstrong et al., 1985, 1987; Palacios et al., 1985), presumably to avoid predation or provide important foraging opportunities.

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Cannibalism limits hatchery production of many fish and crustacean species (Alston, 1991; Hecht and Appelbaum, 1988; Hecht and Pienaar, 1993; Liao et al., 2001; Marshall et al., 2005; Sotelano et al., 2012; Zmora et al., 2005) including king crabs (Daly et al., 2009, 2012). For juvenile red king crabs, most intra-cohort cannibalism occurs immediately following molting when the exoskeleton is soft and provides little anti-predator effects, which can be exacerbated by hatchery conditions. For example, increased molting frequency associated with elevated temperatures causes high rates of cannibalism for red king crabs, especially at high stocking densities (e.g., 2000 crabs m^{-2}) (Daly et al., 2013). Yet the degree of cannibalism in blue king crabs is not well understood, particularly under hatchery conditions. Juvenile blue king crabs grow slower than red king crabs at elevated temperatures (Stoner et al., 2013), thus inter-cohort cannibalism may be less problematic than that of red king crabs. Some evidence shows that cannibalism occurs between blue king crab cohorts (Daly and Long, in review), but recently-settled, year-0 blue king crabs display low incidence of intra-cohort cannibalism compared to red king crabs reared under identical laboratory conditions (Stoner et al., 2013).

Blue king crab stock enhancement programs will likely require annual releases of millions to support a viable fishery (Stevens, 2006b), thus improving nursery technology is necessary and will probably require high-density rearing conditions. Techniques such as size grading, artificial structures, and diet modification can mediate cannibalism and improve hatchery efficiency for juvenile red king crabs (Daly et al., 2009, 2012, 2013; Long et al., 2012; Stoner et al., 2010) and will likely also be required for blue king crabs. Understanding the degree of cannibalism in blue king crabs will inform the development of such technologies and improve hatchery production when considering rearing effort, use of floor space, and economic cost. For example, low rates of cannibalism may allow populations to be cultured at higher densities, while high rates of cannibalism may require populations to be sorted by size and reared at differential densities (Daly et al., 2012). As such, we aimed to evaluate cannibalism during the period immediately after settlement in hatchery grow-out conditions using indoor rearing tanks. We hypothesized that survival would decrease, but overall biomass would increase with increasing stocking density.

2. Materials and methods

2.1. Broodstock and larval rearing

Blue king crab larvae were cultured in collaboration with the Alaska King Crab Research Rehabilitation and Biology (AKCRRAB) program using established rearing techniques (Swingle et al., 2013). Nineteen ovigerous female blue king crabs were captured with baited commercial pots near Saint Matthew Island, Alaska, USA in November 2011 and transported to the Alutiiq Pride Shellfish Hatchery in Seward, Alaska where they were placed in 2000 L tanks containing flow-through ambient seawater and fed 20 g chopped herring and squid per crab twice per week. Larvae were cultured in 190 L cylindroconical tanks at 25 larvae L^{-1} with flow-through seawater heated to approximately 10 °C. Zoeal larvae were daily fed San Francisco Bay strain *Artemia* nauplii (2 *Artemia* ml^{-1}), which were enriched with DC DHA Selco® (INVE Aquaculture, UT, USA) enrichment media in 100 L cylindrical tanks for 24 h. *Artemia* were supplemented with either *Chaetoceros muelleri* microalgae, *Thalassiosira weissflogii* microalgae, or microalgae concentrate (Shellfish Diet 1800®, Instant Algae®).

2.2. Juvenile nursery conditions

Once post-larvae reached the first juvenile instar stage (C1), they were transferred to nursery tanks. Each tank contained ten flat bottomed 58 cm tall by 58 cm diameter cylindrical containers with a 100 μm mesh screen on the bottom, a surface area of approximately 0.25 m^2, and volume of approximately 65 L, hereafter called silos. Ten silos were placed in each of two larger 3200 L rectangular tanks. Crabs were stocked in the silos at densities of 500, 1000, 2000, 4000, and 6000 crabs m^{-2}. Density treatments had four replicates, which were randomly assigned among tanks. All the silos contained equal amounts (approximately 100 g (0.88 m^2)) of commercial fishing gillnets (7.6 cm mesh size). The gillnet twine consisted of nine woven nylon monofilaments for a total diameter of approximately 1.0 mm and surface area of 88 cm^2 g^{-1}. Gillnet improves survival by providing complex structures with interstitial spaces reducing crab contact with each other (Daly et al., 2009). All the silos were supplied with flow-through ambient seawater entering from the top with a flow rate of approximately 1.5 L min^{-1}. Incoming seawater was sourced from a deep-water (~75 m) intake and filtered to 5 μm, UV sterilized, and carbon filtered. Temperature was maintained at approximately 10 °C.

The crabs were fed a mixed diet of commercially available feeds including Cyclop-eeze® (Argent Chemical Laboratories, WA, USA), frozen enriched *Artemia* nauplii, Zeigler™ (Zeigler Bros, Inc., PA, USA) shrimp feed, and Otohime B1 and B2 (Reed Mariculture, CA, USA). Cyclop-eeze® is a frozen copepod (~800 μm length) high in carotenoids and omega-3 highly unsaturated fatty acids (HUFAs). Otohime B is a high protein diet developed for marine fish and consists of 200–360 μm (B1) and 360–620 μm (B2) sinking pellets. Newly hatched San Francisco Bay strain *Artemia* nauplii (~450 μm length) have high levels of lipids and unsaturated fatty acids. *Artemia* nauplii were enriched with DC DHA Selco® (INVE Aquaculture, UT, USA) enrichment media for 24 h to enhance their nutritional quality and were then frozen. The frozen enriched *Artemia* nauplii (~750 μm length) were negatively buoyant and available for benthic crab consumption. Zeigler™ PL Redi-Reserve commercial shrimp feed (400–600 μm particles) is commonly used in crustacean aquaculture due to its high levels of highly unsaturated fatty acids. Each feed type was alternated daily. Wet feeds (frozen enriched *Artemia*, Cyclop-eeze®) were administered at approximately 20% body wet weight daily, while dry feeds (Zeigler™, Otohime) were administered at approximately 2% body wet weight daily. Uneaten food and waste were siphoned from rearing containers weekly. Exuvia were examined to determine when molting to the next instar stage occurred.

The duration of the experiment was 42 days for comparison to a study that cultured recently-settled red king crabs under identical hatchery grow-out conditions (Daly et al., 2009). The present study was conducted with additional high density treatments (i.e., 4000 and 6000 crabs m^{-2}). The crabs were counted within each replicate at the start and end of the experiment to calculate survival, number of crabs cannibalized, and the proportion of the population cannibalized. Crab biomass was assessed by obtaining a batch wet weight of all crabs in a given replicate.

2.3. Statistical analyses

We compared the results from the present study to those of a prior red king crab hatchery study (Daly et al., 2009) to help understand the differences in optimal nursery rearing conditions between the two species. We used ANCOVA to compare survival, biomass, proportion cannibalized, and number cannibalized between blue and red king crabs with stocking density as a covariate. Significant species × density interactions were evident with the slopes of the linear regressions being different between the species. As such, we ran individual linear regression analyses for the blue and red king crabs separately. We used Shapiro–Wilk and Levene's analyses to test assumptions of normality and equal variances. Survival and proportion cannibalized data were arcsine square root transformed, while biomass data were log transformed to meet these assumptions. Statistics were done in SYSTAT 12.00.08 (Chicago, Illinois USA) and SigmaPlot 12.0 (San Jose, California). Significance for all tests was established with $\alpha = 0.05$.