Feasibility of Offshore Co-culture of Abalone, *Haliotis discus hannai* Ino, and Sea Cucumber, *Apostichopus japonicus*, in a Temperate Zone

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Abstract

Feasibility of offshore co-culture of abalone and sea cucumber was investigated in Northern China. Survival and growth of abalone, *Haliotis discus hannai* Ino, and sea cucumber, *Apostichopus japonicus*, co-cultured in abalone cages from suspended longlines, in the offshore area, were examined. Abalone and sea cucumbers were co-cultured at density ratios of both 3:1 and 6:1 for 1 yr. Abalone were fed with fresh kelp and no additional feed was given to sea cucumbers. Survival of abalone and sea cucumber was 100% for all treatments. Abalone and sea cucumber grew well; the body weight (BW) of abalone and sea cucumber was nearly doubled and had reached a commercial size. There were no significant differences in the growth rates for both abalone and sea cucumber between the two density treatments. The specific growth rate of BW of abalone (SGRbw) was highest in June, with a value of 0.536%/d. Growth rate of sea cucumber (SGRsc) was highest in December, reached 1.84%/d, with an annual average SGRsc of 0.182%/d. Results suggested that the offshore co-culture of abalone and sea cucumber was feasible offshore. The co-culture of abalone with sea cucumbers may provide an additional valuable crop without additional financial input.

Abalone, *Haliotis discus hannai* Ino, is highly valued seafood throughout the world. Extensive culture of abalone has developed rapidly and widely in coastal waters throughout China in the last two decades. The majority of *H. discus hannai* is cultured in suspended cages on suspended longlines in the nearshore shallow water, with water depth around 7–8 m.
Abalone is cultured in high densities to maximize the utilization of the limited nearshore waters. For example, in North China, the abalone is usually cultured more than 900,000 individuals/ha. In North China, abalone are fed with fresh kelp *Saccharina japonica*. Abalone farming produces large quantities of uneaten kelp and abalone feces, which are deposited on the bottom of the sea and lead to an organic enrichment in the surface sediment. This self-pollution of abalone culture was exacerbated by the poor diffusion of metabolic wastes because of the lower water current and the lower level of water exchange in the nearshore. Mass mortalities of abalone are frequently recorded during the summer seasons, which could be as high as 60%. Anoxia caused by water column stratification and benthic organic matter decomposition is believed to be a possible reason.

The self-pollution of abalone aquaculture could be reduced via the development of integrated multitrophic aquaculture (IMTA) farming pattern by introducing the deposit-feeding sea cucumber to the abalone monoculture system. Sea cucumbers can feed on sediment with organic matter and play a key role in reducing nutrient loads to the environment (Ahlgren 1998; Michio et al. 2003; Yu et al. 2013). It was reported that the dissolved nitrogen in the water of abalone tanks was reduced when co-cultured with sea cucumber, mainly because the organic matter was ingested and assimilated by the sea cucumber (Kang et al. 2003; Wang et al. 2007).

The sea cucumber, *Apostichopus japonicus* (Selenka) is a common species in shallow waters along eastern Asian coasts from 35°N to at least 44°N (Liao 2001). *A. japonicus* is a highly valued aquaculture species in China and Southeast Asia. Existence of cultured animals at different trophic levels can be the basis of environment-friendly polyculture systems (Neori et al. 2004). The feeding habit and commercial value of *A. japonicus* make it a potential candidate for IMTA. If the sea cucumber co-cultured with the abalone, is capable of surviving and growing by consuming the abalone feces and other organic debris from the cultivation cage, then the harmful materials can be turned into a marketable product (sea cucumber biomass). Theoretically, with the harvest of the sea cucumbers, the nutrients (e.g., C, N, and P) can be removed from the culture system.

In recent years, there has been a trend for aquaculture expanding toward offshore because of the rapid development of the intensive aquaculture; the nearshore coastal waters suitable for abalone culture are very limited. However, it should be noticed that the offshore natural condition is very different from that of nearshore waters, for example, the water is much deeper and water current is much stronger in the offshore area. The aquaculture pattern and equipments applied in the nearshore waters may not suitable in the offshore environment. Nevertheless, generally, the information regarding aquaculture in deep water is relatively limited (Paltzat et al. 2008).

Fang et al. (2009) reported that the sea cucumber can survive and grow well when co-cultured in abalone cages from suspended longlines in the nearshore water. However, until now, in China, the aquaculture activities of abalone and sea cucumber were seldom tried in offshore areas. It was thought that the stronger water currents in the offshore environment may impede the normal feeding behaviors of abalone and sea cucumber. Nonetheless, this is only based on anecdotal evidence and there is no field experiment designed specially to examine the feasibility of offshore culture of abalone and sea cucumber. Whether they can survive and grow in the offshore water, and whether the offshore co-culture of sea cucumbers in abalone cages is feasible are unclear.

The objectives of this study were to investigate the survival and growth of abalone and sea cucumber offshore and to test the feasibility of offshore co-culture of abalone and sea cucumber in abalone cages from suspended longlines. Such knowledge would be useful for the aquaculture industry to move or expand the abalone and sea cucumber cultivation from nearshore to offshore and for the development of an effective IMTA system.
Materials and Methods

Experimental Area

The experiment was conducted in Sanggou Bay, a 140-km² coastal embayment in North China (37°01′–37°09′N and 122°24′–122°35′E), from April 15, 2008, to May 10, 2009. Water exchange between the bay and the Yellow Sea is driven by semi-diurnal tidal exchange (tidal range 2 m). The average depth of the bay is about 8.0 m, with the 5-m isobaths approaching the seashore. According to the definition of Fang (unpublished), aquaculture in water that is deeper than 30 m or is more than three nautical miles offshore is defined as offshore marine culture. The experimental farming area (37°07′N and 122°36′E) was located five nautical miles offshore, where the water depth was approximately 40 m. The peak flow of the water current in this area was approximately 1 m/sec. The experimental area was located in an offshore kelp, S. japonica, culture area, which was managed by Xunshan Fisheries Corporation, one of the biggest sea kelp culture corporations in China.

Experimental Animals and Culturing Condition

A total of 216 hatchery-reared abalone (∼2 yr old) with an initial shell length (SL) of 75.98 ± 2.22 mm and an initial body weight (BW) of 62.43 ± 2.18 g were used in the experiment. The abalone were distributed randomly among six cuboid plastic cages ($L \times W \times H = 50 \times 40 \times 120$ cm) (36 abalone per cage). Each cage has six layers (Fig. 1). Fifty-four cucumbers (initial BW 25.3 ± 2.68 g) were collected by divers from the shallow sea of a nearshore bottom-culture farm. Two density ratios of abalone to sea cucumber (6:1 and 3:1, based on the number of individual animals) were designed by placing one or two sea cucumbers in each layer of abalone cages, respectively. Survival and growth of the sea cucumbers and abalone in each layer were measured individually. Each density ratio treatment has three replicates ($n = 3$ cages per treatment). The experimental cages were randomly suspended from longlines underneath the kelp at a depth of 4.5 m.

Experimental Procedure

Considering that the experimental abalone and sea cucumbers were collected from nearshore area, prior to the start of the experiment, the animals were acclimated for 1 mo
(March to April 2008) to avoid recording the effects of a change of living condition. BW and SL of each abalone and sea cucumber were measured at the end of the acclimation period. The wet weight of sea cucumbers in each layer was measured within 90 sec after the animal was taken out of the seawater and superfluous external water was removed with a sponge. No marked decrease in wet weight was observed by extending the time (ca. 3 min) out of water to allow water expulsion of sea cucumbers from their cloaca and coelomic cavity. There was no significant difference in the BW and SL of abalone and sea cucumber among the treatment groups at the end of the acclimation \( (P > 0.05) \). Abalone were fed with more than a sufficient amount of fresh kelp weekly. The same amount of kelp was given to each cage. No additional food was given to the sea cucumbers. BW of each sea cucumber was measured monthly (or bimonthly from June to October to avoid the harmful effects of high temperature).

As there was a large variation in the body length of the sea cucumber, the body length was not used as a growth parameter in this study. Abalone are usually adhered to the cage wall very tightly and removing them from the cage is harmful to them. To avoid interfering with them, the measurements were performed with longer time intervals to minimize the injury to the abalone. The growth parameter of abalone and sea cucumber was measured at the end of the experiment. Prior to weighing, excess water was removed by blotting with tissue paper. During the experiment, surface water temperature was monitored.

**Calculations and Statistical Analysis**

The following variables were calculated:

Survival \( (\%) = \frac{n}{N} \times 100 \)

Daily increase in body weight (DIBW, g)
\[ = \frac{(W_t - W_0)}{t} \]

Daily increase in shell length (DISL, mm)
\[ = \frac{(L_t - L_0)}{t} \]

Specific growth rate of body weight
\[ (\text{SGRbw, } \% / d) = \frac{\ln (W_t / W_0)}{t} \times 100 \]

Specific growth rate of shell length
\[ (\text{SGRsl, } \% / d) = \frac{\ln (L_t / L_0)}{t} \times 100 \]

where \( n \) is the number of abalone or sea cucumber in each cultivation cage at the end of the experiment, \( N \) the number of abalone or sea cucumber in each cultivation cage at the start of the experiment (individual), \( W_0 \) the mean initial BW of abalone or sea cucumber, \( W_t \) the mean final BW of abalone or sea cucumber (g), \( L_0 \) the mean initial SL of abalone, \( L_t \) the mean final SL of abalone (mm) and \( t \) is the experimental duration (d).

Comparisons in the survival, DIBW, and DISL among the two density treatments were analyzed using \( t \) tests. The statistical significance was set at \( P < 0.05 \). Data are reported as the mean ± standard error (SE). All statistical analysis was performed using Statistica 6.0 (Statsoft, Tulsa, OK, USA).

**Results**

**Survival and Growth of Abalone**

During the experiment, surface water temperature in Sanggou Bay changed greatly. The temperature ranged from 4.2 to 20.6 C, highest in August and lowest in February (Fig. 3). The survival rate of abalone was 100% for all treatment groups (Table 1). There was no significant difference in the growth for abalone between the two density treatments \( (P > 0.05) \) (Table 1). The changing pattern of specific growth rate of abalone BW (SGRbw) was in accordance with the variation of the water temperature (Fig. 2). SGRbw increased from 0.148%/d in May to 0.536%/d in June, and then declined to 0.107 and 0.104%/d in November and May 2009, respectively (Fig. 2A). The specific growth rate of abalone SL (SGRsl) continually declined in each measuring interval. The highest SGRsl was observed in May 2008 reaching 0.0787%/d (Fig. 2B).
Table 1. Mean final body weight and shell length, growth, and survival of abalone and sea cucumber co-cultured in offshore cages at Sanggou Bay.

| Species         | Density treatments | Mean final body weight (g) | Mean final shell length (mm) | DIBW (g/d) | DISL (mm/d) | SGRbw (%/d) | SGRsl (%/d) | Survival (%) |
|-----------------|--------------------|---------------------------|-------------------------------|------------|-------------|--------------|--------------|--------------|
| Abalone         | A : S = 3:1        | 103.00 ± 10.16            | 88.08 ± 5.10                 | 0.124 ± 0.011 | 0.035 ± 0.007 | 0.155 ± 0.009 | 0.121 ± 0.008 | 100          |
|                 | A : S = 6:1        | 101.26 ± 8.64             | 88.22 ± 4.32                 | 0.120 ± 0.009 | 0.035 ± 0.006 | 0.160 ± 0.012 | 0.118 ± 0.013 | 100          |
| Sea cucumber    | A : S = 3:1        | 47.88 ± 6.22              | 0.065 ± 0.006                | /          | /           | 0.182 ± 0.009 | /            | 100          |
|                 | A : S = 6:1        | 48.07 ± 4.38              | 0.065 ± 0.003                | /          | /           | 0.181 ± 0.013 | /            | 100          |

/ = means not measured; A : S = abalone : sea cucumber; DIBW = daily increase in body weight; DISL = daily increase in shell length; SGRbw = specific growth rate of body weight; SGRsl = specific growth rate of shell length.

Data are reported as the mean ± standard error (SE) (n = 3).

Figure 2. Temporal variations in the mean specific growth rate of abalone body weight (SGRbw) (A), shell length (SGRsl) (B), and water temperature in the offshore co-culture system of abalone and sea cucumber over the 1-yr period. Vertical lines represent standard error.

Survival and Growth of Sea Cucumber

No sea cucumber mortality occurred for all treatment groups (Table 1). There was no significant difference in the growth for sea cucumber between the two density treatments ($P > 0.05$) (Table 1). The BW of sea cucumber decreased continually from May to November, and then increased until May 2009. The lowest and highest BWs were observed in November 2008 and April 2009, respectively (Fig. 3A). Weight loss happened from June to October (Fig. 3B). Water temperature during this period was higher than 12°C. Growth was observed from November 2008 to April 2009 (Fig. 3B). Maximum growth rate of sea cucumber was recorded in December, with
high growth rate also in January. The specific growth rates of BW (SGRsc) in these 2 mo were 1.84 and 0.94%/d, and the water temperature was 7.4 and 5.4°C, respectively (Fig. 3B).

Discussion

Offshore Performance of Abalone

The results of the field experiment showed that the abalone could survive and grow well in the offshore (Table 1). Moreover, there appears to be a growth advantage for abalone in the offshore than that in nearshore. Qi et al. (2010) studied the growth of abalone in the nearshore area of Sanggou Bay. The abalone used in their experiment was from the same stock and was of a similar size (≈2 yr old, initial BW 62.31 ± 2.68 g, and initial SL 75.78 ± 2.62 mm) to those used in this study. Both studies fed experimental abalone with kelp, *S. japonica*. The average daily
increase of BW (DIBW) and SL (DISL) of abalone cultured in the offshore area were 0.124 g/d and 0.035 mm/d, respectively (Table 1), higher than that in the nearshore area, which were 0.105 g/d and 0.022 mm/d, respectively (Qi et al. 2010). Moreover, their nearshore experiment was carried out during the summer season, from May to September, when the growth of abalone was higher than the annual average in North China (Nie and Yan 1985; Nie et al. 1996). The abalone growth rate in this study was the average values for the 1-yr period. Therefore, the growth advantage in offshore would be much more evident if the growth rates for the same periods were compared.

The higher growth of abalone in the offshore probably attributed to a better living condition. First, the abalone metabolic waste such as dissolved nitrogen and phosphorus can be diluted more quickly by the stronger water currents in an offshore environment than in the nearshore area. Second, the organic matter produced during abalone culture, for example, uneaten feed and abalone feces, could be ingested and assimilated by sea cucumber. Theoretically, by co-culture and harvesting the sea cucumbers, the nutrients (e.g., C, N, and P) can be removed from the culture system and the negative effects of abalone culture on the environment could be alleviated (Yingst 1976; Kang et al. 2003; Wang et al. 2007). This was partially demonstrated by the findings in the co-culture system of bivalves (e.g., mussel and scallop) and sea cucumber (Zhou et al. 2006; Paltzat et al. 2008; Slater and Carton 2009; Zamora and Jeffs 2011).

Offshore Performance of Sea Cucumber

The results show that sea cucumber could survive and grow well when co-cultured in abalone cages, suggesting that abalone cages can provide a good habitat for sea cucumbers. It is difficult to compare the growth with prior studies because of the wide range of culture conditions, densities, and initial stocking sizes used in different studies, and the various methods used to measure weight (Battaglene et al. 1999). In this study, the SGRbw of sea cucumber in December was 1.84%/d, comparable with that of the same species in a static tank culture system (Kang et al. 2003; Dong et al. 2005), and in scallop cultivation lantern net in the sea averaged 1.60%/d (Zhou et al. 2006). Slater and Carton (2007) reported that when polyculture with green-lipped mussel at the density of 2.5 and 5 ind/m², growth of the sea cucumber, Australostichopus mollis, averaged 0.065 g/d. This was comparable with the growth rates (0.065 g/d) observed in this study (Table 1).

It has been reported that sea cucumber becomes inactive when water temperature exceeds 18 C and will fall into aestivation at water temperatures about 20–24.5 C (Liu et al. 1996; Michio et al. 2003). In this experiment, BW of sea cucumber decreased from June to October, when the water temperature was ranged from 15.6 to 20.6 C, probably because of the inactive or aestivation activities (Fig. 3A). Yang et al. (2005) reported that the optimum temperature for food consumption and growth of sea cucumber under laboratory conditions was between 14 and 15 C. However, inconsistent with their findings, in this experiment, the highest growth rate (SGRsc) was found during December, when the water temperature was 7.4 C (Fig. 3). The differences in growth performances between field study and laboratory experiment suggested that apart from water temperature, food availability may be an important factor that influences the growth of sea cucumber, especially in natural conditions. The food for the sea cucumbers in the abalone cages may be composed of abalone feces, uneaten kelp, and natural sediment. During December, because of the low water temperature, the feeding and metabolic activities of abalone were relatively low. Therefore, the amount of abalone feces was also low. The natural sediment may be a main food resource that supported the growth of sea cucumber. During the experiment, it was observed that a large amount of natural sediment was deposited in the abalone cages. The natural sediment was more available during winter, mainly because the higher resuspension rate resulted from the stronger winds. This was demonstrated by Mao
et al. (2006), who found that the water transparency in December was the lowest and the total particulate mass in winter was relatively very high in Sanggou Bay.

**Production Profit Analysis of Co-culture of Abalone and Sea Cucumber**

The rearing conditions and feeding regimes in this experiment were similar to those used in the majority of commercial enterprises to ensure the results were applicable to commercial culture operations. The price of abalone and sea cucumber was about 160 and 200 RMB/kg (based on fresh weight), respectively, in 2010. The price of juvenile sea cucumber was about 3 RMB per individual. The commercial size of abalone and sea cucumber was about 100 g (fresh weight). Under the culture condition of this experiment, the income of abalone culture was approximately 576 RMB per cage. If the cucumber was co-cultured for two individuals per layer in abalone cages, the value of sea cucumber was about 240 RMB per cage. This represents an increase of approximately 35.4% in abalone culture profit. This indicated that production profit of abalone aquaculture could be enhanced by co-culture and harvesting of sea cucumbers without additional financial input.

**Conclusions**

In conclusion, this field study showed that both the abalone and sea cucumber could survive and grow well in the offshore water. At the end of the study, the BWs of abalone and sea cucumber were nearly doubled and had reached a commercial size. The results suggested that the offshore co-culture of abalone and sea cucumber in suspended abalone cages from longlines is feasible in Sanggou Bay. Co-culture of sea cucumbers in abalone cages may provide an additional valuable crop without additional financial input. Therefore, economic advantages can be achieved by integrating the deposit-feeder cultivation with abalone aquaculture.

Further studies are recommended to determine the optimal number of sea cucumbers co-cultured with abalone, although this study has shown that at least 12 *A. japonicus* can be cultured in each abalone cage. Also, because adult abalone and sea cucumber were used in this study, further studies are recommended to test the performance of juvenile abalone and sea cucumber in the offshore area. In addition, experiments in larger scale and higher replication are needed to determine the commercial suitability of offshore culture with these two species before the techniques are fully industrialized.

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