Available online at www.sciencedirect.com
ScienceDirect
Aquaculture 275 (2008) 124–137
Aquaculture
www.elsevier.com/locate/aqua-online

Growth and production of California sea cucumbers (*Parastichopus californicus* Stimpson) co-cultured with suspended Pacific oysters (*Crassostrea gigas* Thunberg)

D.L. Paltzat [a,c], C.M. Pearce [a,*], P.A. Barnes [b], R.S. McKinley [c]

[a] *Fisheries and Oceans Canada, Pacific Biological Station, 3190 Hammond Bay Road, Nanaimo, British Columbia, Canada V9T 6N7*
[b] *Centre for Shellfish Research, Malaspina University-College, 900 Fifth Street, Nanaimo, British Columbia, Canada V9R 5S5*
[c] *Centre for Aquaculture and Environmental Research, University of British Columbia/Fisheries and Oceans Canada, 4160 Marine Drive, Vancouver, British Columbia, Canada V7V 1N6*

Received 3 January 2007; received in revised form 14 December 2007; accepted 17 December 2007

Abstract

Growth and production of California sea cucumbers (*Parastichopus californicus* Stimpson), co-cultured with suspended Pacific oysters (*Crassostrea gigas* Thunberg), were investigated in a 12-month (January 2004–January 2005) study conducted at two sites of deep-water, suspended oyster culture in British Columbia, Canada. Rates of oyster biodeposition (faeces and pseudofaeces) and the utilization of this particulate material as a food source by *P. californicus* were also examined. Peaks in sedimentation rates through 8.5 m water depth, below the oyster rafts, were observed in April (93.6 g dry wt m^{-2} d^{-1}) and July (91.9 g dry wt m^{-2} d^{-1}) 2004. At the two study sites, maximum mean total organic carbon deposition rate at 8.5 m depth occurred in July 2004 and amounted to 3123 and 3830 mg dry wt C m^{-2} d^{-1}. Maximum mean total nitrogen deposition rate at the two sites was 524 and 568 mg dry wt N m^{-2} d^{-1} which occurred in November and July 2004, respectively. Mean C/N ratios of particulate material in the sediment trap samples collected at the two sites between January and November 2004 ranged between 5.9 and 12.4 and may be considered to be of high nutritional value. Growth and survivorship of sea cucumbers held in experimental trays below the suspended oysters were measured, growth being assessed using split weight as well as muscle and skin wet weights. There were no sea cucumber mortalities in any of the trays deployed at either site during the study. Sea cucumbers grown in trays at both sites successfully utilized biodeposits from the cultured oysters and showed a mean weight increase of 42.9 g in approximately 12 months (average growth rates at both sites ranged from 0.061 to 0.158 g d^{-1}). Overall growth was affected by the absence of visceral organs and the cessation of feeding activity observed in the November 2004 sampling period. Overall mean values (for the two study sites) for organic content were significantly higher in the foregut of the sea cucumbers (24.7 % or 224.6 mg g^{-1} dry sediment) than in the sediment (5.9% or 51.6 mg g^{-1} dry sediment) or in the hindgut (14.5% or 157.9 mg g^{-1} dry sediment), showing both active selection of organic material from the sediments and digestion/assimilation of these organics in the gut. Organic material deposited in the trays was assimilated by *P. californicus* at the two study sites with an average efficiency of 40.4%. The successful utilization of the naturally-available biodeposits from the cultured Pacific oysters by California sea cucumbers suggests the feasibility of developing a commercial-scale co-culture system that would both reduce the amount of organic deposition underneath shellfish farms and produce a secondary cash crop.

Keywords: Biodeposits; California sea cucumber; *Parastichopus californicus*; Deposit feeding; Integrated multi-trophic aquaculture; Pacific oyster; *Crassostrea gigas*

1. Introduction

Dense assemblages of filter-feeding bivalves enhance the vertical flow of organic matter towards the benthic environment. Many studies report that bivalves in suspended raft or long-line culture play a key role in coastal ecosystems due to their high filtration capacity and culture density (e.g. Kautsky and Evans, 1987; Jaramillo et al., 1992; Hatcher et al., 1994). Bivalves, to a large extent, remove small suspended particles and initiate the sedimentation of larger particles of high organic content (i.e. faeces and pseudofaeces) (Kautsky and Evans, 1987). Captured particles

* Corresponding author. Tel.: +1 250 756 3352; fax: +1 250 756 7053.
E-mail address: PearceC@pac.dfo-mpo.gc.ca (C.M. Pearce).

0044-8486/$ - see front matter.
doi:10.1016/j.aquaculture.2007.12.014

are rejected before ingestion as pseudofaeces or ingested, passed through the digestive tract, and excreted as faeces (collectively termed biodeposits) (Haven and Morales-Alamo, 1966; Navarro and Thompson, 1997; Miller et al., 2002). Although there is no net addition of organic matter, the larger biodeposits become available as an energy source (i.e. carbon and nitrogen) to micro-organisms, and ultimately to higher trophic levels such as benthic macro-invertebrates (Yingst, 1976; Dame and Dankers, 1988).

Soft-sediment communities are often dominated by deposit feeders and the physical and chemical characteristics of the sediments are influenced by the feeding activities of these animals. Like many deposit-feeding organisms, sea cucumbers exploit the sediment layer with the highest and most readily utilizable organic matter (Yingst, 1982). The California sea cucumber (*Parastichopus californicus* Stimpson) occurs in low intertidal and subtidal areas on rock, shell or muddy–sandy sediments or on pilings, and reaches greatest densities in quieter waters from Baja California to the Gulf of Alaska (Cameron and Fankboner, 1989; Kozloff, 1996; Lambert, 1997). This sea cucumber species has become the focus of a limited commercial dive fishery in British Columbia, Washington, and Alaska (Sloan, 1986; Cameron and Fankboner, 1989; Conand and Byrne, 1993) and is highly valued for import into, and re-export from, Hong Kong. Like many other commercially important sea cucumber species, *P. californicus* has previously been fished extensively in British Columbia and Washington to meet the increased demand for its longitudinal muscles and bêche-de-mer, the market name for the dried product from the body wall of holothurians, in southeast Asia (Conand and Byrne, 1993). An early period of growth in capacity and landings in the 1980s led to over-exploitation of the fishery in British Columbia.

Oyster growers in British Columbia have found that juveniles and sub-adults of *P. californicus* can form a significant population within the community of organisms that settle and grow on the oyster culture gear (B. Stevenson, Viking Bay Ventures, pers. comm.). The sea cucumbers have been observed to clean the detritus from the oysters and ingest the organic material (D. Paltzat, pers. obs.). The organic matter deposited by the shellfish as faeces and pseudofaeces may represent a significant proportion of the energy (Stuart et al., 1982) potentially available to *P. californicus* in the vicinity of oyster farms. Ahlgren (1998) showed that muscle development of California sea cucumbers reared inside floating net pens at a salmon (*Oncorhynchus* sp.) rearing facility in southeast Alaska was significantly greater than that of sea cucumbers feeding in their natural environment. That work suggests that this species of sea cucumber is capable of consuming fouling debris (e.g. fish faeces, excess fish food, algae, etc.) and could turn harmful fouling into a marketable product (sea cucumber biomass). Integrated multi-trophic aquaculture (IMTA) has the potential to increase the efficiency and productivity of intensive monoculture systems while reducing waste loadings and environmental impacts (Chopin et al., 2001; Neori et al., 2004). IMTA technology has been applied to sea cucumber production in China where *Stichopus* (=*Apostichopus*) *japonicus*, the temperate species in the western Pacific, has been successfully grown, without supplemental feeding, on artificial reefs placed in shrimp ponds (Chen, 2003). However, in other parts of the world, suitable culture methods for commercially exploited sea cucumber species have not yet been developed or are in experimental stages (Hagen, 1996; Ramofafia et al., 1997; Kang et al., 2003).

In the present study, field investigations were undertaken to examine the feasibility of growing California sea cucumbers, *P. californicus*, in co-culture with Pacific oysters, *Crassostrea gigas* (Thunberg), the oyster species farmed in British Columbia. Sedimentation rates of biodeposits from the cultured oysters were determined and samples of the particulate material were analyzed for organic carbon and nitrogen content. Utilization of this material as a food source by *P. californicus* was measured quarterly over a 12-month period by monitoring growth (i.e. changes in overall weight and muscle and skin wet weights) and survivorship of the sea cucumbers *in situ* under oyster culture rafts.

2. Materials and methods

2.1. Study sites

Field studies were conducted at two established *C. gigas* culture sites in Village Bay (VB), Quadra Island (49°59′N, 124°11′W) and Gorge Harbour (GH), Cortes Island (50°05′N, 125°01′W), British Columbia (Fig. 1). At the farms, oysters are cultured on strings suspended from rafts in the upper 6 m (approximately) of the water column at an average density of 1077 individuals m^{-2}. Approximately 15 dozen oysters are cultured on each string and the rafts contain 250 strings (ca. 45,000 individuals per raft) (J. Rendall, Bee Islets Co-op, pers. comm.). The two study sites were approximately 17 km apart. Village Bay is relatively exposed and has direct tidal flushing from the Strait of Georgia. The oyster farm in VB is located in the northwest section of the bay which reaches a maximum depth of 19 m. The farm produces both raft and long-line cultured oysters. The site contains 36 rafts which cover a surface area of approximately 1500 m^2 as well as long-lines, near the back of the bay. Gorge Harbour is a semi-restricted water body, with tidal exchange from the Strait of Georgia occurring through a single narrow opening along the southwest shore of the embayment. The basin in GH is depositional and has a maximum depth of 30 m around the oyster farm. Tidal ranges of 1–2 m and tidal current velocities of 16.0–37.5 cm s^{-1} and 7.5–10.0 cm s^{-1} in surface and deeper (13–15 m) waters, respectively, have been documented for GH (Hay and Company Consultants, Inc., 2001; Richardson and Newell, 2002). The oyster rafts used at this study site were located in the Bee Islets lease, which contains approximately 150 rafts covering a surface area of ca. 44,800 m^2 (J. Rendall, Bee Islets Co-op, pers. comm.).

2.2. Water column characteristics

As part of a concurrent ecological study conducted by the Centre for Shellfish Research (CSR), Malaspina University-College, submersible temperature data loggers (Onset Computer Corporation, Pocasset, MA, USA) were suspended for 14 months below a central experimental oyster raft at both study sites. The temperature data loggers were positioned at four depths: 3.0, 5.0, 8.5, and 10.0 m at VB and 3.0, 8.5, 18.5, and 23.5 m at GH. Water temperature measurements were recorded every 15 min by the moored instruments except for breaks when the data were downloaded during each of the quarterly sampling periods. Also in conjunction with the CSR's concurrent ecological interactions study, water column profiles were run at both sites on sampling dates in January, April, and July 2004 to determine salinity and chlorophyll (*a*, *b*, and *c1*+*c2*) using a YSI 6600 multi-parameter water-quality monitoring sonde (YSI Inc., Yellow Springs, OH, USA). Values for salinity and chlorophyll are reported at depths of approximately 8.5 m in January, 8.0 m in April, and 10.1 m in July 2004. These correspond to depths at which sediment traps were placed and the depth at which sea cucumbers were held.

2.3. Sea cucumber growth and production

Sub-adult sea cucumbers (contracted length: 8–13 cm) for the field studies were collected from the oyster farms at VB and GH. Animals were taken directly off the