*Journal of Shellfish Research*, Vol. 31, No. 1, 13–20, 2012.

# GROWTH OF THE WINGED PEARL OYSTER, *PTERIA PENGUIN*, AT DISSIMILAR SITES IN NORTHEASTERN AUSTRALIA

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***ABSTRACT*** Growth of *Pteria penguin* pearl oysters was monitored for 20 mo, from April 2009 to November 2010, to investigate differences in growth performance at three dissimilar sites: Pioneer Bay, Cape Ferguson, and Horseshoe Bay in the Great Barrier Reef lagoon. Growth parameters generated with the von Bertalanffy growth function ranged from $K = 0.09–0.32$ and $L_\infty = 283.6–822.5$. Overall growth performance ($\Phi'$) ranged from 4.40–4.77. Time to reach commercial size ($T_{100}$) was between 1.38 y and 1.54 y, and $T_{120}$ was between 1.74 and 1.92 y. A more accurate estimate of the $L_\infty = 213.4$-mm dorsoventral measurement (DVM) was obtained at Pioneer Bay by using a larger data set that incorporated a wider size range of oysters. Overall monthly increase in DVM of oysters held at Horseshoe Bay (5.3 ± 0.2 mm) was more than that at Pioneer Bay (4.7 ± 0.2 mm) and Cape Ferguson (4.9 ± 0.2 mm), and there were significant differences in the monthly DVM increase among the sites during growth measurement periods ($P < 0.05$). Monthly DVM growth was fastest (7.2 ± 0.2 mm) in small oysters (DVM, 50–70 mm) in the spring and summer and was lowest (2.4 ± 0.4 mm) in larger oysters (DVM, 105–110 mm) during the spring. Regression analysis showed anteroposterior measurement (APM), shell thickness (ST), and whole weight (WW) were significantly correlated with DVM for all groups ($P < 0.001$). In the commercial size class of 100–120 mm DVM, mean WW of oysters at Cape Ferguson was significantly greater ($P < 0.01$), and the APM-to-DVM ratio was also significantly greater for oysters at Cape Ferguson and Horseshoe Bay ($P < 0.01$), whereas there were no significant differences among groups with regard to the ST-to-DVM ratio. At all 3 sites, the highest mortalities (measured as a percentage) were recorded for small oysters (DVM, 25–50 mm) during the winter period. Suspended particulate inorganic matter (measured in grams) levels were significantly different among sites ($P < 0.001$). Comparison among growth rates obtained during this study demonstrate that there is significant variability in growth between sites in the Great Barrier Reef lagoon, and that *P. penguin* are able to tolerate—and even thrive—under a wide range of turbidity levels.

***KEY WORDS:*** pearl oyster, *Pteria penguin*, modeling, PIM, morphometrics, DVM, sites

## INTRODUCTION

The winged pearl oyster, *Pteria penguin* (Röding 1798), is cultured throughout Southeast Asia, in parts of northern Australia, and in some Pacific island nations (Southgate et al. 2008). However this species has received relatively little research attention, and not much is known about its culture requirements, suitable environmental conditions to optimize growth, and the time required to reach a size suitable for nucleus implanting. Information on the growth performance of *P. penguin* cultured under different environmental conditions is of interest to pearl farmers, as it provides a comparative indicator of the suitability of sites for culture of this species, and shell growth rates also provide information related to pearl growth, as shell increment and nacre deposition are positively correlated (Coeroli & Mizuno 1985). Traditionally, *P. penguin* have been used to produce semi-spherical pearls, known as mabé (Gervis & Sims 1992), although more recently, increasing round pearl production from this species has been undertaken (Farell et al. 1994, Yu & Wang 2004). Mabé nucleus implants are inserted in oysters at or above 100 mm shell height, or dorsoventral measurement (DVM) (Kripa et al. 2008), whereas for round pearl production, oysters with a DVM ranging from 110–140 mm are used (Mao et al. 2004).

The growth rates of marine bivalves are directly related to age (Bayne & Newell 1983). Shell or somatic tissue growth begins to decrease in larger animals, when there is a shift in the allocation of energy toward reproductive effort (Saucedo & Southgate 2008). The von Bertalanffy growth function (VBGF) has been used to describe the relationship between age and shell height, or DVM, in a number of pearl oyster species (Saucedo & Southgate 2008). The VGBF calculates the parameter $L\infty$, which is interpreted as the maximum mean shell height, or DVM, attained, and $K$ is the growth coefficient that determines how fast an oyster approaches $L\infty$ (Bertalanffy 1938, Bertalanffy 1957). The growth index, $\Phi'$, is also used in many studies to compare growth performance between oysters held at different sites (Saucedo & Southgate 2008). Another index, $T$, calculates the time required for oysters to reach commercial size. For example, for *Pinctada maxima* (Jameson, 1901), $T_{120}$ denotes the time required to reach a DVM of 120 mm, a size suitable for pearl production in this species (Yukihira et al. 2006).

Studies of comparative growth can be used to determine optimal sites for culturing oysters at different phases during the production cycle. High-growth sites are favored for growing oysters to commercial size more rapidly, whereas low-growth sites are preferred before and after nucleus insertion, to condition oysters prior to seeding and to improve pearl quality by slower deposition of nacre (Saucedo & Southgate 2008). In this study, growth of *P. penguin* cultured at 3 different sites was investigated to determine whether there were differences in growth performance of oysters between sites, to determine the time required to reach commercial size at each site, and to generate information on the influence of environmental factors on the growth rate of this species.

## MATERIALS AND METHODS

### *Study Sites*

The three culture sites used in this study were situated within the Great Barrier Reef lagoon: (1) Pioneer Bay, Orpheus Island;

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DOI: 10.2983/035.031.0102

(2) Cape Ferguson, Bowling Green Bay; and (3) Horseshoe Bay, Magnetic Island (Fig. 1). Pioneer Bay is a natural habitat of *P. penguin*, located 17 km east of the mainland coast, approximately 80 km north of Townsville. Oysters at this site were suspended from a longline situated 50 m from the edge of a fringing coral reef with a coral and rubble substrate underneath. Of the 3 sites used in this study, Pioneer Bay is situated farthest away from the coast and presents relatively oligotrophic water quality conditions compared with Cape Ferguson and Horseshoe Bay (De'ath 2007). The oysters at Cape Ferguson were suspended from a wharf at the Australian Institute of Marine Science, situated in a sheltered bay on the coast, 50 km south of Townsville. Cape Ferguson sits within Bowling Green Bay, in an extensive area of coastal mangroves and mudflats. Freshwater river discharges during periods of intense monsoon rains (from November to May) can cause marked drops in salinity and high levels of active silt deposition at this site (Queensland Parks and Wildlife Service 2000, Devlin & Brodie 2005). High levels of turbidity are recorded at the wharf site when wave action resuspends fine material from the bottom (Yukihira et al. 1999). Horseshoe Bay at Magnetic Island is situated approximately 15 km from the mainland coast, north of Townsville. The oysters at this site were suspended from a longline that lies adjacent to a reef flat. Horseshoe Bay also experiences high turbidity levels associated with river discharge, and wind-driven wave action that resuspends sediments (Devlin & Brodie 2005), although to a lesser extent than at Cape Ferguson. Nutrient concentrations in the Great Barrier Reef lagoon follow seasonal patterns, with peak levels recorded in the summer months and lower levels (by up to 50%) recorded in the winter (De'ath 2007).

#### *Measurement of Oyster Growth*

All *P. penguin* ($n$ = 370) used in this study were field specimens captured on spat collectors on the floating longline at James Cook University's Research Station at Orpheus Island, northeast Queensland (18°61′ S, 146°49′ E). The juvenile oysters that were used to compare growth among sites were captured in February to March, during the 2009 spawning season ($n$ = 280; initial mean DVM, 24.5 ± 0.5 mm). These oysters were divided randomly into 3 groups and held at 3 sites for 20 mo, from April 2009 to November 2010. Growth data from a larger group of oysters captured during the 2008 spawning season were also included in the study ($n$ = 90; initial mean DVM, 38.2 ± 1.1 mm). All oysters were held at a depth of 3 m in panel nets, which consisted of frames (90 × 40 cm) covered with plastic mesh sewn to form individual pockets for each oyster. At each site, the groups of oysters were held in 8 replicate nets containing between 10–12 oysters. Oysters were cleaned, weighed, and measured every 2–3 mo over 7 growth measurement periods (10 growth periods for the larger cohort), and mortalities were also recorded for each of the growth measurement periods: April to July 2009, July to October 2009, October 2009 to January 2010, January to April 2010, April to June 2010, June to August 2010, and August to November 2010. Shell growth dimensions were measured to the nearest 0.1 mm using calipers to record: (1) the DVM, the greatest dorsoventral distance measured at a right angle to the hinge line; (2) the anteroposterior measurement (APM), the greatest distance between the anterior and posterior margins of the shell, parallel to the hinge line; and (3) shell thickness (ST), the greatest distance between the external surfaces of the 2 valves when closed (Hynd 1955) (Fig. 2). Whole weight (WW) of the oysters was also recorded to the nearest 0.1 g.

#### *Particulate Inorganic Matter*

Sediment traps were used to collect suspended particulate matter samples at each of the sites during each growth measurement period (English et al. 1997). The traps consisted of five duplicate PVC cylinders at each site, 11.5 cm long × 5 cm internal diameter, with one end capped and baffles at the top to deter settlement of fish and other organisms. Sediment traps were fastened vertically with cable ties to the frames holding the oysters. The traps were removed at each oyster measurement time, and the contents were rinsed into water sample bottles. Sediment samples and water in the bottles were vacuum pumped

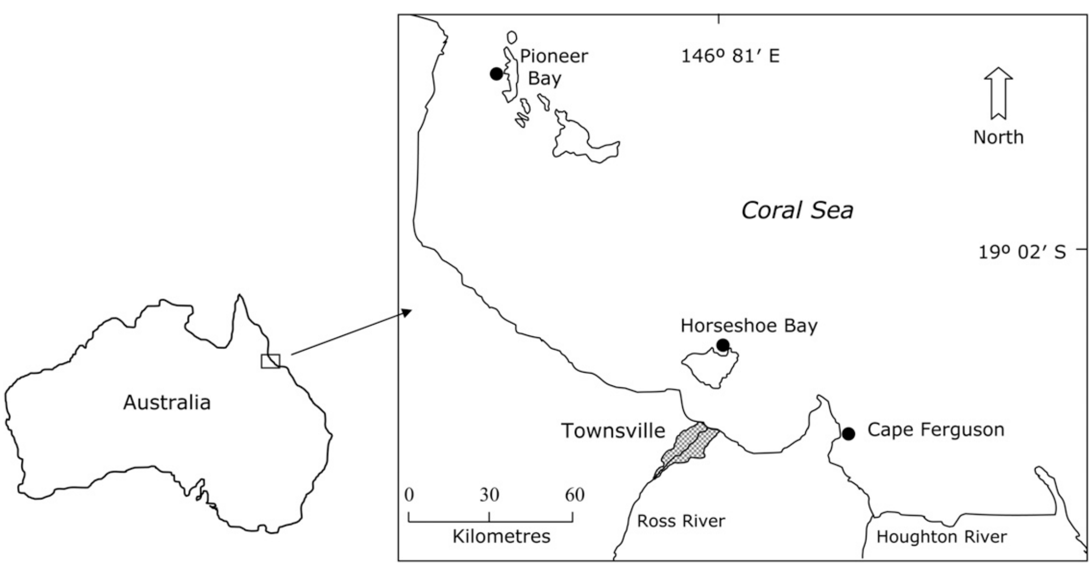


**Figure 1. Location of 3 sites used for experimental culture of *Pteria penguin* in northeastern Queensland, Australia.**

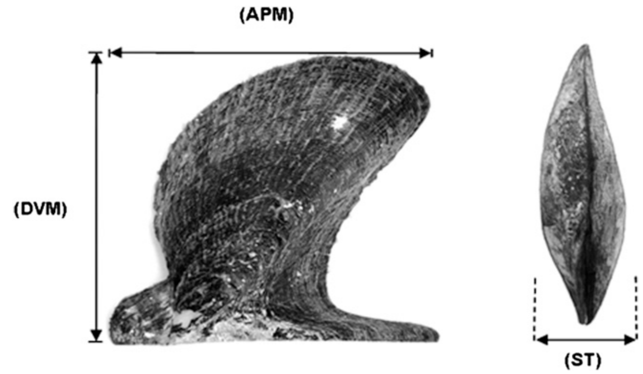


**Figure 2. Shell measurements of *Pteria penguin* monitored during this study. APM, anteroposterior measurement; DVM, dorsoventral measurement; ST, shell thickness.**

onto filter paper, and the contents were dried at 60°C for 48 h, then were weighed, "ashed" at 500°C for 24 h, and reweighed to determine the relative ratios of suspended particulate matter (measured in grams) and particulate inorganic matter (PIM; measured in grams) for each sample. Salinity data for Cape Ferguson were provided by the Australian Institute of Marine Science.

### *Data Analyses*

Shell DVM is considered the best indicator of growth performance in pearl oysters (Sims 1993). Shell DVM-at-age data were fitted to the special VBGF $L(t) = L_\infty[1 - e^{-Kt}]$, using the least squares curve fit function in MATLAB, version 7.9.0. $L_\infty$ is the asymptotic length (in millimeters), and $K$ is the growth coefficient per year, which measures the exponential rate of approach to the asymptotic size. Juvenile cohorts in this study were limited to oysters between 1.6 y and 1.9 y of age. The growth data from a larger cohort of oysters held at Pioneer Bay that had reached 2.7 y were pooled with the smaller cohort at that site, and a growth curve was computed using the special VBGF. The 2 groups of oysters at Pioneer Bay were held under the same conditions, and differed only in age. An index of overall growth performance developed by Pauly and Munro (1984), which incorporates both $K$ and $L_\infty$ ($\Phi' = \log_{10} K + 2 \times \log_{10} L_\infty$), was used to evaluate growth performance of oysters among sites. Time to reach commercial size, $T_{100}$ and $T_{120}$, was also calculated to determine the time required for oysters at each site to reach 100 mm and 120 mm DVM, respectively—sizes suitable for mabé pearl production and round pearl production, respectively (Mao et al. 2004, Kripa et al. 2008).

Mean monthly DVM increase of oysters was calculated for each measurement period and checked for normality (Kolmogorov-Smirnov test) and homogeneity of variance (Levene's test). One-way ANOVA and Tukey's test for post hoc analyses were used to compare mean monthly DVM increases for each measurement period, and also mean WW and mean APM-to-DVM and ST-to-DVM ratios within the commercial size range of 100–120 mm DVM. The relationship between the morphometric parameters—APM, ST, and WW to DVM—were examined by regression analysis (Milione & Southgate 2011b). Kruskal-Wallis nonparametric analysis was used to compare mean PIM (measured in grams) among sites for each measurement period. Statistical analyses of DVM growth data and PIM samples were performed with SPSS (IBM SPSS Statistics, version 19), with $P = 0.05$.

## RESULTS

### *Monthly Growth*

Monthly changes in mean DVM for the 3 groups of juvenile oysters, combined, increased rapidly at the beginning of the study, rising from 4.4 ± 0.2 mm/mo in May to July 2009 to 7.2 ± 0.2 mm/mo in January 2010, then declined to the lowest level recorded (2.4 ± 0.2 mm/mo) in larger oysters in November 2010. At the end of the study, overall DVM increase was greatest in oysters held at Horseshoe Bay (5.3 ± 0.2 mm/mo), intermediate at Cape Ferguson (4.9 ± 0.2 mm), and lowest at Pioneer Bay (4.7 ± 0.2 mm). Monthly DVM increase varied significantly among oysters held at different sites during 5 of the 7 growth measurement periods, with those at Horseshoe Bay frequently showing the highest growth rates ($P < 0.05$; Fig. 3). Overall survival at the end of the study was greatest for oysters at Cape Ferguson (90%), intermediate at Pioneer Bay (82%), and lowest for oysters held at Horseshoe Bay (69%). At all 3 sites, the highest mortalities were recorded for young oysters in May to October 2009.

### *Particulate Inorganic Matter*

Mean PIM levels (measured in grams per month) throughout the study period were 1.68 ± 0.13 g/mo at Pioneer Bay, 20.15 ± 2.02 g/mo at Cape Ferguson, and 8.59 ± 0.81 g/mo at Horseshoe Bay. Mean PIM levels differed significantly among sites ($P < 0.001$), and there were significant differences in mean PIM among sites for all measurement periods ($P < 0.001$; Fig. 4).

### *VBGF Growth Parameters*

The results of the von Bertalanffy model applied to the growth data from the smaller oysters held at 3 sites, as well as the combined growth data from two age cohorts at Pioneer Bay, are shown in Table 1. Time to reach commercial size ($T_{100}$) was least at Cape Ferguson (1.38 y) and longest (1.67 y) for the combined size classes at Pioneer Bay. The lowest $\Phi'$ value (4.23) was obtained from the combined growth data for the small and large oysters held at Pioneer Bay, whereas the highest value for this growth index (4.77) was computed for oysters at Horseshoe Bay. Predicted $L_\infty$ values for the small cohorts deviated considerably from the known $L_{max}$ for this species (DVM, 212 mm). However, the $L_\infty$ value of 213.4 mm predicted from the pooled growth data at Pioneer Bay deviated only marginally from $L_{max}$. The VBGF growth curves for the smaller cohorts of *P. penguin* held at 3 sites and the combined groups at Pioneer Bay are shown in Figures 5 and 6.

### *Morphometric Relationships*

The relationships between APM, ST, and WW to DVM were all significant in all groups (Table 2). Within the DVM size class 100–120 mm, there were no significant differences in the mean ST-to-DVM ratios among sites. However, mean APM-to-DVM was significantly greater at Cape Ferguson and Horseshoe Bay than at Pioneer Bay ($P < 0.01$), and mean WW of oysters was significantly greater at Cape Ferguson ($P < 0.01$; Table 3).

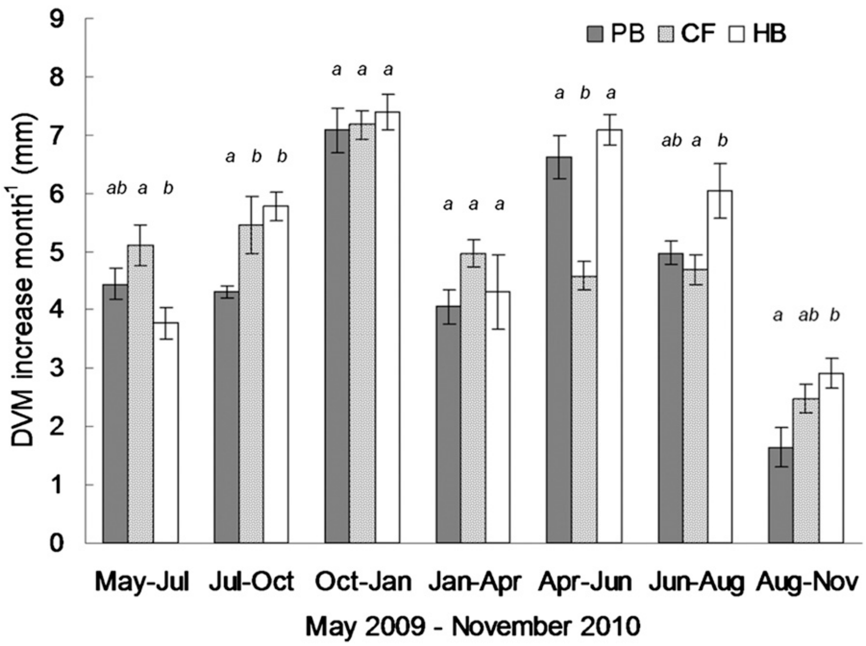


**Figure 3. Mean dorsoventral measurement (DVM) increase per month of *Pteria penguin* cultured at Pioneer Bay (PB), Cape Ferguson (CF), and Horseshoe Bay (HB). Statistical comparisons were made among the 3 sites for each of the 7 growth periods. Columns in the same measurement period with the same superscript do not differ significantly.**

## DISCUSSION

In this study, the most accurate estimate of $L_\infty = 213$ mm DVM for *P. penguin* (with the smallest deviation from $L_{max}$ of 1.4 mm) was obtained by using growth data of oysters up to 2.7 y of age, ranging in size from 89.7–153.0 mm in the final measurement period. The estimates of $L_\infty$ for small-oyster cohorts at Pioneer Bay, Cape Ferguson, and Horseshoe Bay of 283.6, 362.3, and 822.5 mm DVM, respectively, deviated substantially from the maximum size observed in field specimens (DVM, 212 mm) and from the reported maximum size for *P. penguin* of up to 210 mm DVM (Lamprell & Healy 1998). Substantial variability in reported $L_\infty$ values both within and between studies on the same species are not uncommon. Overestimated $L_\infty$ values have been reported for *Pinctada imbricata* (Röding, 1798), $L_\infty = 162.7$ (Urban 2002); *Pinctada margaritifera* (Linnaeus, 1758), $L_\infty = 310$ (Sims 1994); and *Pinctada fucata* (Gould, 1850), $L_\infty = 600.9$ (Yassein et al. 2000) (Table 4). The mean maximum theoretical size calculated with the VBGF may diverge considerably from the true maximum size if the data provided are not extensive enough to demonstrate asymptotic growth (Knight 1968). This explains why the VBGF estimates of $L_\infty$ made with growth data from the three younger cohorts in this study did not produce an accurate model of size at maturity.

Because of the inverse relationship between $L_\infty$ and $K$, overestimates of $L_\infty$ for the younger cohorts mean that $K$ was also underestimated for these groups. Using the growth index $\Phi'$ to compare the different growth sets of the smaller oysters, our results indicated that oysters at Horseshoe Bay presented the best overall growth performance ($\Phi' = 4.77$). This was also

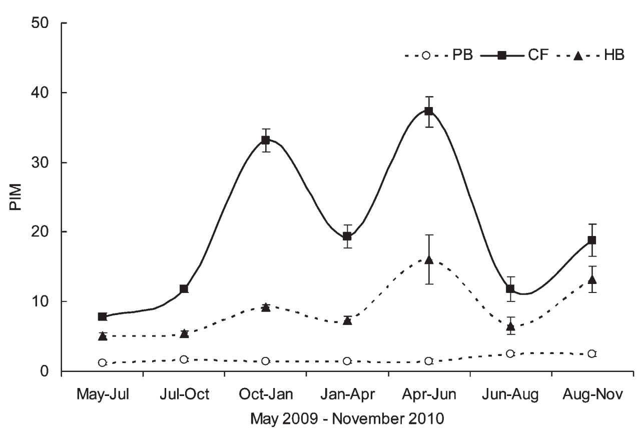


**Figure 4. Mean particulate inorganic matter (PIM) per month (±1 SE; in grams) at Pioneer Bay (PB), Cape Ferguson (CF), and Horseshoe Bay (HB).**

**TABLE 1.**

**Growth parameter estimates of von Bertalanffy model for groups of winged pearl oysters (*Pteria penguin*) held at 3 sites.**

| Site | Size Group | $K$/y | $L_\infty$ (mm) | Dev | $T_{100}$ (y) | $T_{120}$ (y) | $\Phi'$ |
|---|---|---|---|---|---|---|---|
| Pioneer Bay | Small | 0.21 | 362.3 | 150.3 | 1.54 | 1.92 | 4.44 |
| Cape Ferguson | Small | 0.32 | 283.6 | 71.6 | 1.38 | 1.74 | 4.40 |
| Horseshoe Bay | Small | 0.09 | 822.5 | 610.5 | 1.49 | 1.81 | 4.77 |
| Pioneer Bay | Small and large | 0.38 | 213.4 | 1.4 | 1.67 | 2.19 | 4.23 |

Dev, $\sqrt{(L_\infty - L_{max})^2}$, ($L_{max} = 212$ mm); $K$, growth coefficient; $L_\infty$, asymptotic dorsoventral measurement; $T_{100}$ and $T_{120}$, estimated time to reach commercial size (100 mm and 120 mm, respectively); $\Phi'$, growth performance index.

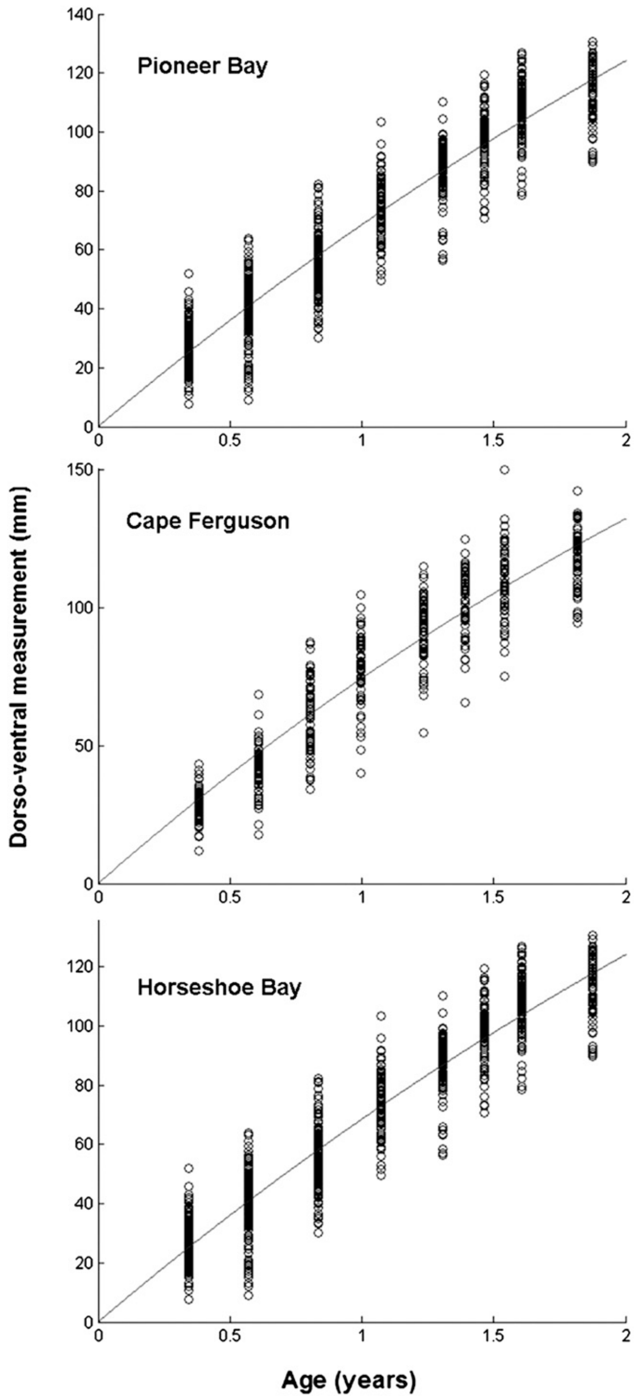


**Figure 5. Shell dorsoventral measurement and computed von Bertalanffy growth curves for juvenile *Pteria penguin* held at 3 sites: Pioneer Bay, Cape Ferguson, and Horseshoe Bay.**

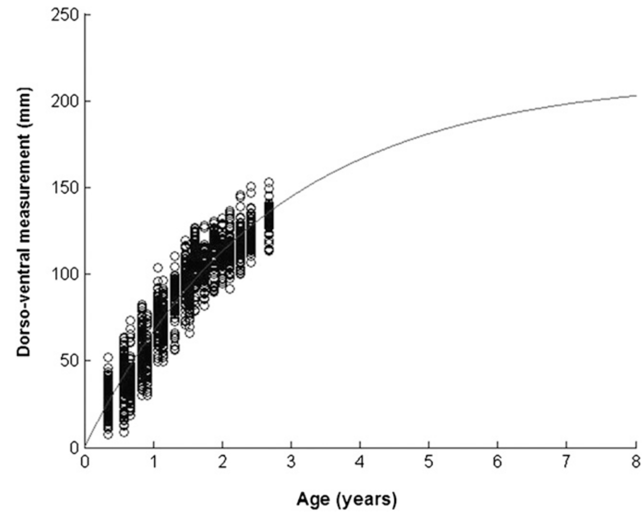


**Figure 6. Shell dorsoventral measurement and computed von Bertalanffy growth curve for 2 cohorts (small and large) of *Pteria penguin* plotted against age.**

reflected in the analysis of the monthly DVM increment, which showed that the overall increase in DVM was greatest at Horseshoe Bay, and it was also greatest at this site during 5 of the 7 growth measurement periods. Estimates of time to reach commercial size in the juvenile cohorts also showed that *P. penguin* presents a relatively fast growth rate ($T_{100}$ ranged from 1.38–1.54 y and $T_{120}$ ranged from 1.74–1.92 y). By comparison, $T_{120}$ for *P. maxima* was 1.9 y at Cape Ferguson and 2.1 y at Pioneer Bay; for *P. margaritifera,* $T_{120}$ was 2.5 y at Pioneer Bay and 3.9 y at Cape Ferguson (Yukihira et al. 2006). However, mortalities were highest at Horseshoe Bay, and occurred mainly during periods of severe biofouling infestation at this site, particularly from settlement of barnacles on the nets. Biofouling has been linked to stunted growth and higher mortality in cultured bivalves (Denys & Ison 2008). Survival in oysters at Horseshoe Bay would probably have been increased by applying more frequent cleaning of shells during the summer, from December to January.

A number of studies on pearl oysters have described progressive changes that occur in the form of the shell during the course of the life cycle, such as in *P. fucata* (Alagarswami & Chellam 1977, Yoo et al. 1986, Mohamed et al. 2006, Hwang et al. 2007), *P. sterna* (Gould, 1851) and *Pinctada mazatlanica* (Hanley, 1856) (Gaytan-Mondragon et al. 1993, Saucedo et al. 1998), *P. margaritifera* (Sims 1993, Pouvreau et al. 2000, Hwang et al. 2007) and *P. penguin* (Milione & Southgate 2011b). It is theorized that bivalves exposed to differing environmental conditions during growth, such as food availability, water temperature, depth, and wave action, among other factors, may display differences in the morphometric ratios between shell dimensions and/or shell dimensions and weight (Dame 1972, Brown & Hartwick 1988). Observed differences in morphometric relationships between populations in different localities may also be the result of adaptations through successive generations (Galtsoff 1964), and therefore these differences may not become manifest in newly translocated animals.

The relative shell dimensions of pearl oysters—in particular, ST—can be a limiting factor on the size and/or the number of the nuclei that can be implanted, and thus the size and/or number of pearls produced (Wada 1984, Mohamed et al. 2006). Thus morphometric relationships between groups of *P. penguin* reared under different environmental conditions were also compared in this study. Previous morphometric studies on pearl oysters cultured in different environments have reported significant differences between calculated regression coefficients for the relationship between APM and DVM and for ST and

**TABLE 2.**

**Regression statistics for whole weight (WW) and dorsoventral measurement (DVM), anteroposterior measurement (APM) and DVM, and shell thickness (ST) and DVM for *Pteria penguin* held at 3 sites.**

| Parameter | Site | Equation | $r^2$ | *P* |
|---|---|---|---|---|
| WW | Pioneer Bay | $y = 0.0002x^{2.85}$ | 0.97 | 0.000 |
| | Cape Ferguson | $y = 0.0005x^{2.70}$ | 0.98 | 0.000 |
| | Horseshoe Bay | $y = 0.0004x^{2.70}$ | 0.98 | 0.000 |
| APM | Pioneer Bay | $y = 19.79 + 0.93x$ | 0.91 | 0.000 |
| | Cape Ferguson | $y = 23.82 + 0.92x$ | 0.92 | 0.000 |
| | Horseshoe Bay | $y = 11.11 + 1.06x$ | 0.97 | 0.000 |
| ST | Pioneer Bay | $y = 0.12 + 0.30x$ | 0.93 | 0.000 |
| | Cape Ferguson | $y = 1.35 + 0.29x$ | 0.94 | 0.000 |
| | Horseshoe Bay | $y = 0.09 + 0.31x$ | 0.98 | 0.000 |

DVM (or other growth parameters) in different size classes (Alagarswami & Chellam 1977, Yoo et al. 1986, Mohamed et al. 2006, Hwang et al. 2007). However absolute differences in the relative ratios of APM-to-DVM or ST-to-DVM between groups of oysters held under differing site conditions have not been shown. Sims (1993) reported significant differences in the ratio of DVM-to-heel depth between groups of *P. margaritifera*, but it is unclear whether relative heel depth has relevance for nuclei insertion procedures. On the other hand, Taylor et al. (1997) demonstrated that the APM-to-DVM ratio differed significantly between oysters held at different stocking densities, but in this case the independent variable was related to culture method, not environment per se. This raises the question of whether varying culture method could be used as a means to grow oysters with a greater ST-to-DVM ratio. There were significant differences found in this study in the ratios of APM-to-DVM for oysters within the commercial size range of 100–120 mm DVM at Cape Ferguson and Horseshoe Bay, and in mean WW of oysters held at Cape Ferguson, which suggests the possibility of selective breeding of oysters at these sites as a means to improve morphometric relationships. Continued monitoring of the morphometric relationships in these oysters further over time and also in successive generations is required.

Faster DVM increase observed during the earlier stages of the study and slower growth rates observed at all 3 sites during the final growth period were expected as a result of rapid growth during the juvenile phase and the onset of reproductive activity

**TABLE 3.**

**Mean (± 1 SE) morphometric measurements for *Pteria penguin* within size range 100–120 mm DVM at three sites.**

| Site | WW (g) | APM-to-DVM Ratio | ST-to-DVM Ratio |
|---|---|---|---|
| Pioneer Bay | 139.3 ± 2.3[a] | 1.090 ± 0.01[a] | 0.301 ± 0.002[a] |
| Cape Ferguson | 152.2 ± 2.5[b] | 1.135 ± 0.01[b] | 0.303 ± 0.002[a] |
| Horseshoe Bay | 136.1 ± 2.7[a] | 1.145 ± 0.02[b] | 0.304 ± 0.00[a] |

Rows with the same superscript do not differ significantly.
APM, anteroposterior measurement; DVM, dorsoventral measurement; ST, shell thickness; WW, whole weight.

in the larger animals (Southgate & Lucas 2003). The sharp decrease in growth recorded at all sites between January to April 2010 was anomalous, however—caused by inclement weather in early February 2010. During this time, parts of the floating longline at Horseshoe Bay were damaged, and the normal peak in spat harvest at Pioneer Bay was decimated (Milione & Southgate 2011a). Growth during this period would usually be expected to have continued vigorously, as seawater temperature and food concentrations are generally favorable (i.e., highest) at this time (De'ath 2007), and a return to higher growth rates was seen during the following measurement period.

For the most part, higher monthly DVM growth rates among the 3 smaller groups of oysters were observed at Horseshoe Bay and Cape Ferguson, indicating that conditions at these sites are generally more favorable for growth of *P. penguin*. A notable exception to this was observed at Cape Ferguson during April to June 2010, when oysters did not return to vigorous growth after the decrease seen in January to April, suggesting that the adverse environmental conditions of the preceding measurement period may have had a chronic impact or persisted longer at this site. It is unlikely that the high PIM levels at Cape Ferguson during this period were responsible for the reduced growth, as mean PIM per month was equally high during October to January, when DVM growth rate peaked at this site. Of the 3 sites, Cape Ferguson is exposed to greater fluctuations in salinity resulting from its proximity to freshwater runoff from nearby creeks and rivers (Devlin & Brodie 2005), and this may have been an important contributing factor to the decreased growth at Cape Ferguson. Mean monthly salinity at Cape Ferguson from September 2009 to January 2010 ranged from 34.6–36.1‰, but decreased during February to 29.4 ± 0.1 (range, 25.6–31.8‰ (AIMS, unpubl. data).

Pearl oyster growth rates are strongly influenced by the quantity and the quality of the food particles that are available to them, as well as their ability to ingest and digest the particles (Lucas 2008). The highest PIM levels in this study were recorded at Cape Ferguson, resulting from the combination of shallow water and wave action generated by strong winds, which suspends benthic materials, such as silt, benthic algae, and deposited detritus at this site (Yukihira et al. 1999). In this study, the concurrent higher PIM levels and DVM increase observed at Horseshoe Bay and at Cape Ferguson compared with Pioneer Bay indicate that *P. penguin* is able to tolerate and even thrive in environments with relatively high PIM levels, possibly as a result of its capacity to derive higher nutrient uptake under these conditions. In some bivalves, suspended silt in the water column can result in an increase in the assimilation of ingested algae (Bayne & Newell 1983) or can stimulate feeding activity (Winter 1976, Møhlenberg & Kiørboe 1981). Published data on the particle size ingestion capacity of *P. penguin*, or its ability to select food particles of higher nutritional quality preferentially from available food sources under natural conditions, is currently lacking.

In summary, our results show the highest overall growth performance was achieved by oysters held at Horseshoe Bay, and the monthly DVM increase here was also generally greater, indicating that sites with relatively high turbidity may promote faster growth in this species compared with more oligotrophic conditions found farther away from the coast. High growth rates were also recorded at Cape Ferguson, although exposure to seasonal freshwater inputs may limit growth at this site during

TABLE 4.

**Von Bertalanffy growth parameters for various species of pearl oyster at different locations.**

| Species | Location | $L_\infty$ | $K$/y | Authors |
|---|---|---|---|---|
| *Pteria sterna* | Mexico | 100 | 0.69 | Saucedo and Monteforte (1997) |
| *Pteria penguin* | Queensland, Australia | 213.4 | 0.38 | Current study |
| *Pinctada maxima* | Cook Islands | 189–266 | 1.10–1.98 | Sims (1993) |
| | Queensland, Australia | 205–229 | 0.39–0.41 | Yukihira et al. (2006) |
| | Western Australia | 194–210 | 0.72–0.79 | Hart and Joll (2006) |
| | West Papua | 168.38 | 0.93 | Lee et al. (2008) |
| *Pinctada margaritifera* | Queensland, Australia | 136–157 | 0.54–0.58 | Yukihira et al. (2006) |
| | French | 160.5 | 0.038 | Pouvreau et al. (2000) |
| | Polynesia | 147–186.5 | 0.42–0.58 | Pouvreau and Prasil (2001) |
| | Cook Islands | 131–310 | 0.162–0.528 | Sims (1993) |
| *Pinctada mazatlanica* | Mexico | 110 | 0.45 | Saucedo and Monteforte (1997) |
| *Pinctada fucata* | India | 79.36 | 0.075/mo | Chellam (1988) |
| *Pinctada radiata* (*fucata*) | Arabian Gulf | 132.2 | 0.34 | Mohammed and Yassien (2003) |
| | Qatar | | | |
| | Egyptian | 600.9 | 0.56 | Yassein et al. (2000) |
| | Mediterranean | | | |
| *Pinctada imbricate* (*fucata*) | Venezuela | 85.15 | 1.42 | Marcano et al. (2005) |
| | Columbian | 84 | 0.939 | Urban (2000a) |
| | Caribbean | 63.9–84 | 0.625–1.605 | Urban (2000b) |
| | | 162.7 | 0.365 | Urban (2002) |

the monsoon season. The findings of this study have implications for selection of sites for achieving rapid growth of juvenile *P. penguin* up to commercial (pearl-producing) size.

## ACKNOWLEDGMENTS

This study was supported by the School of Marine and Tropical Biology at James Cook University, and was conducted as part of the Australian Centre for International Agricultural Research (ACIAR) Project FIS/2006/172 "Winged Pearl Oyster Industry Development in Tonga," for which James Cook University is the commissioned organization. Thanks to Greg Boyle for assistance with MATLAB, and to Paul Rigby from AIMS Long-term Monitoring and Data Centre for providing water quality data, and the reviewers of this paper for their comments and suggestions.

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