# Length-weight relationship, growth and mortality of *Anadara granosa* in Penang Island, Malaysia: an approach using length-frequency data sets

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Length-weight relationship, growth parameters and mortality rates of *Anadara granosa* in the intertidal zone of Balik Pulau, Penang Island, West Coast of Malaysia were investigated based on monthly length-frequency data (December 2011 to November 2012). A total of 548 individuals ranging from 11.25 to 33.13 mm size were subjected to analysis. Logarithmic relationship between the length and weight was Log $W = 2.328$ Log $L - 2.537$ ($R^2 = 0.922$) for combined sexes. From this equation it was clear that the exponent '$b$' value for *A. granosa* showed a negative allometric growth ($b < 3$). A von Bertalanffy growth function with an asymptotic length ($L_\infty$) of 35.40 mm and a growth constant ($K$) of 1.1 year$^{-1}$ was established from length frequency distributions. The $t_o$ (0.140) was estimated by substituting the $L_\infty$ and $K$ in the Pauly's equation. The sizes attained by *A. granosa* were 10.13, 14.36, 17.89, 20.82, 23.56 and 25.29 mm at the end of 2, 4, 6, 8, 10 and 12 months, respectively. The estimated growth performance index (Ø) was 3.13 while the estimated lifespan of the cockles was about 2.72 years at the study area. The estimated value of total mortality based on length-converted catch curve was $Z = 3.02$ year$^{-1}$. The natural mortality ($M$) and fishing mortality ($F$) rates were 1.84 and 0.48 year$^{-1}$, respectively. The exploitation level ($E$) of *A. granosa* was 0.20, which indicated slight fishing pressure on the stock.

## INTRODUCTION

Cockles are ideal candidates for fisheries because of the fast growth rate, continuous reproduction throughout the year and high population abundance. Among cockles, *Anadara granosa* (Linnaeus 1758) of the family Arcidae is a commercially valuable species due to human consumption in Peninsular Malaysia (Vakily, 1992). *Anadara granosa* is exploited from both natural populations and as a farming resource. The commercial exploitation of this species in Malaysia began in 1948 in Perak, Malaysia. It has recently been extensively cultivated on several mudflats on the west coast of Malaysia such as Kedah (Merbok), Pulau Pinang (Juru), Perak (Kuala Gula, Kuala Sangga-Matang, Kuala Trong, Sg. Jarum), Selangor (Kuala Selangor) and Johor (Muar) (Izura & Hooi, 2008). *Anadara granosa* aquaculture is an important fishery in the inshore waters of Malaysia. *Anadara granosa* production contributed more than 50% to the national aquaculture production where Malaysia was ranked 5th in Asia Pacific with 78,712 tons in 2002 (Sugiyama *et al.*, 2004). Cockle aquaculture in Penang

makes the area the third largest producer of cockles in the west coast of peninsular Malaysia (Hassan, 2004).

Apart from the preliminary study of *A. granosa* by Broom (1983), there have been some basic studies on the ecology (Afiati, 1994; Brotohadikusomo, 1994), reproductive cycle (Suwanjarat *et al.*, 2009), gonad maturation (Afiati, 2007), growth rate (Din & Ahamad, 1995), mortality and the experimental populations (Broom, 1983) of blood cockles in Malaysia.

Any study on the age and growth rate of *A. granosa* will lead to an understanding regarding the age class, structure of stock, population growth and longevity. Since growth rate in molluscs is described as an increase in total length and body weight, studying them could be the ideal method to estimate growth rate. An analysis of age and growth can be used to describe the effect of environmental factors on growth and the comparison of growth rates in different geographic areas (Ramesh *et al.*, 2009). Although cockles are an important fishery in Malaysia, the population dynamics of this species are poorly known. Detailed information on growth rate and environmental parameters can be obtained from the length frequency of cockles over a period of time.

A number of methods have been used to estimate the age and growth rate of molluscs including the study of annual growth bands on the external surfaces of mollusc shells, determining microgrowth bands in the inner shell layer and mark–recapture experiments. In *A. granosa*, the bands may be missing or difficult to calculate, as in the case of the first-year

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growth bands and the closely packed bands produced later. Therefore, an alternative method, estimating the age at different sizes can be used to analyse the frequency distribution of molluscs over an extended time period (Fiori & Morsán, 2004). Length-frequency data sets include a series of modes, each of which shows one particular age class. A growth model can be estimated with length at different age group using mean mode of each age class in the cockle population. The evolution of continuous data sets from the same population provides a more accurate analysis by using modes through the samples in a time series (Bjorndal et al., 1995).

Information about a variety of population parameters such as asymptotic length ($L_\infty$), growth coefficient ($K$), the mortality (natural and fishing) rate and exploitation level ($E$) are valuable for the evaluation and control of cockle resources (Malathi & Thippeswamy, 2013). Growth and mortality models are important for analytical fisheries management. The evaluation of the age of cockles is needed in order to complete the information about the abundance and fluctuations of any species (El-Haweet et al., 2005). There are several methods to determine the exploitation levels and population dynamics of cockles. FAO-ICLARM Stock Assessment Tools (FiSAT) is commonly used to assess the stock. This method requires length-frequency information (Amin et al., 2001; Vakily, 1992). The main advantage of this method is that during a 1 year study period, with enough available length-frequency information we are able to assess any bivalve stock (Al-Barwani et al., 2007). A length-based stock assessment can be performed by plotting the variation of mean length or mean weight of individuals against age (Gosling, 2008). Although different equations are used to fit curves to the growth parameters, the ideal equation to study the growth rate is the von Bertalanffy growth function because it is used as a sub-model in more complex models which describe population dynamics (Rabaoui et al., 2007).

The main objectives of this study are (1) to determine the relationship between the length and weight of *A. granosa* cultured in Balik Pulau, Penang Island, Malaysia; (2) to confirm the application of length-frequency analysis to provide reliable growth parameters of *A. granosa* during growth, mortality and reproduction cycles in the cockle population; and (3) to ascertain the ageing and growth rate of *A. granosa* in Balik Pulau, Penang Island, Malaysia.

## MATERIALS AND METHODS

### Sample collection

Blood cockles *A. granosa* were collected from the intertidal areas (exposed during all low tides) of Balik Pulau (5°20′05.50″N 100°11′35.32″E), Penang Island, West Coast of Malaysia at monthly intervals from December 2011 to November 2012. A total of 548 individuals of *A. granosa* were collected during the study period and subjected to length measurements (Figure 1).

### Seawater temperature measurement

Daily seawater temperature was measured using a HOBO Pendant Temp/Light logger fixed in the study area. The logger was calibrated to record hourly seawater temperature in the study site for the period between December 2011 and November 2012.

## Length-weight relationship

The length-weight relationship was calculated by measuring the shell length (anterior-posterior axis) to the nearest 0.1 mm by Vernier callipers, while the total weight was calculated for each individual by digital balance to the nearest 0.001 g.

The length-weight relationship was estimated by using the allometric equation $W = aL^b$ (Quinn II & Deriso, 1999; Vieira et al., 2014), where $W$ is the weight (g) and $L$ is the total length (mm) of *A. granosa*, '$a$' is the intercept (initial growth coefficient) and '$b$' is the slope and relative growth rates of the variables. The '$a$' and '$b$' parameters were calculated using regression analysis of log-log transformed data:

$$\text{Log } W = \text{Log } a + b \text{ Log } L$$

The correlation ($r^2$), which is the level of relationship between the length and weight, was calculated from the linear analysis. The 95% confidence intervals for b (CI 95%) were calculated to determine differences of growth coefficient ($b$) from 3.0. If $b = 3.0$, growth is isometric, however if $b > 3.0$, growth is positive allometric. Growth is negative allometric when $b < 3.0$.

## Estimation of growth parameters

The length-frequency records were arranged into 10 mm class intervals from December 2011 to November 2012. Length frequency data analysis was carried out by Electronic Length Frequency Analysis (ELEFAN I) following the FiSAT package. Growth parameters including asymptotic length ($L_\infty$) and growth coefficient ($K$) were obtained by ELEFAN I.

## The von Bertalanffy growth model

The von Bertalanffy Growth Function (VBGF) was used to obtain the size of the *A. granosa* at various ages. The von Bertalanffy equation was fitted to calculate the length-at-age curve by using the non-linear squares estimation method (Pauly et al., 1992). The von Bertalanffy function can be described by the following equation (Mohammadikia et al., 2014):

$$L_t = L_\infty (1 - \exp[-K^{(t-t_0)}])$$

$L_\infty$ = Asymptotic length ($L_\infty$), $K$ = Growth coefficient, $L_t$ = Length at age '$t$', $t_0$ = Hypothetical age at which the length is 0.

The ELEFAN method is unable to calculate the $t_0$ value through the length frequency records, an acceptable value of '$t_0$' was predicted by Pauly (1983) by replacing the $L_\infty$ (mm) and $K$ (year$^{-1}$) in the following function (Kuganathan, 2006):

$$\text{Log}(-t_0) \approx -0.3922 - 0.2752 \log L_\infty - 1.038 \log K$$

$L_\infty$ and $K$ selected from the compilation of length growth parameters so as to cover a wide diversity of taxa and size.
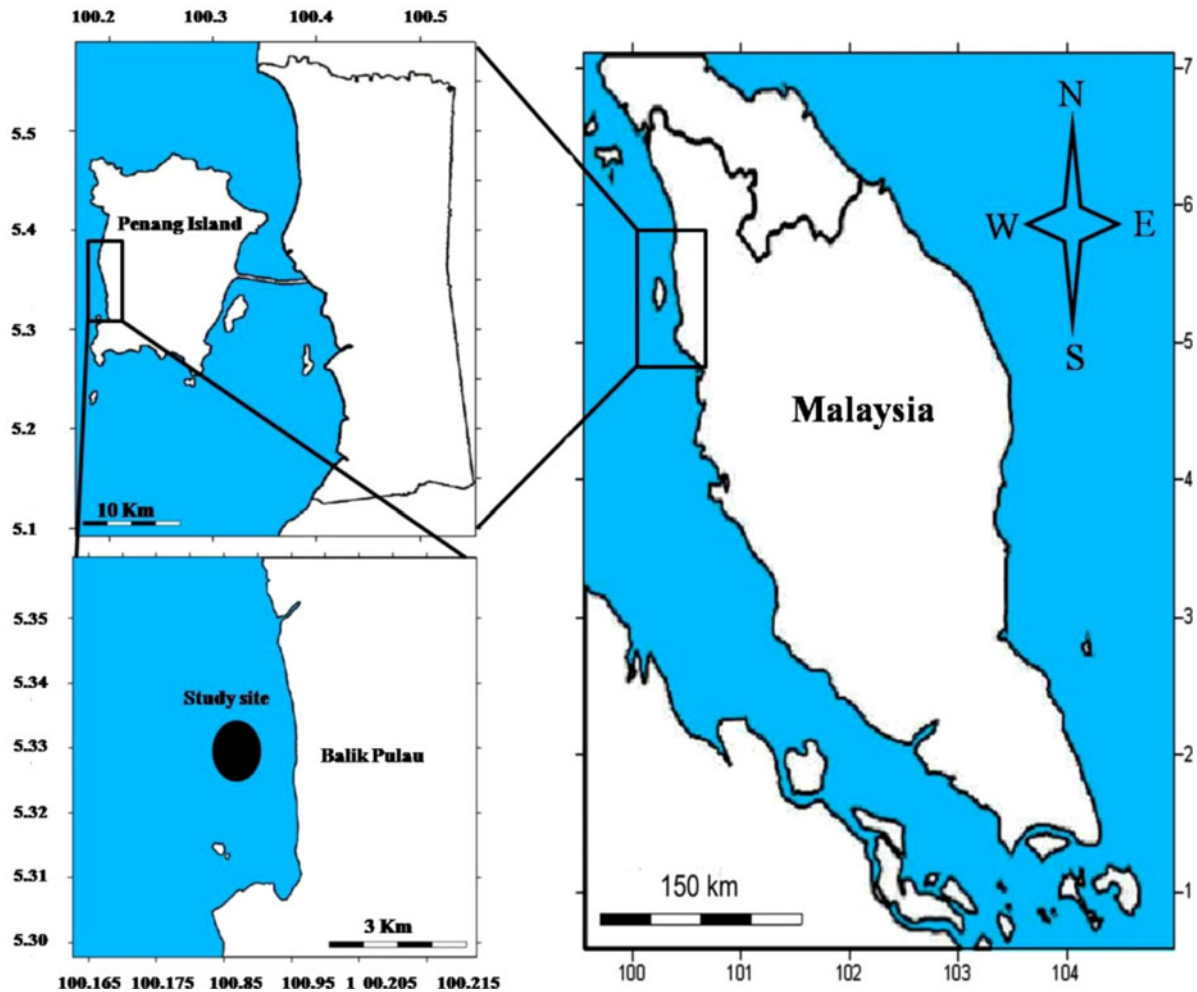
**Fig. 1.** Location of *Anadara granosa* study site, Penang Island, West Coast of Peninsular Malaysia.

## Growth performance index (Ø)

The growth performance index (Ø) was estimated using the Pauly & Munro ([1984](#)) method with asymptotic length ($L_\infty$) and growth coefficient ($K$).

$$(\text{Ø}) = \log K + 2 \log L_\infty$$

## Potential longevity

The potential longevity ($t_{\max}$) of *A. granosa* was obtained from the Pauly ([1983](#)) equation:

$$t_{\max} = \frac{3}{K}$$

$t_{\max}$: The approximate maximum age *A. granosa* in a given population will reach.

## Mortality coefficients

Mortality coefficients such as total mortality ($Z$), natural mortality ($M$), fishing mortality ($F$) and exploitation rate ($E$) were calculated using FiSAT software and the steady-state sample method (Gayanilo, [1997](#); Cikes Kec & Zorica, [2013](#)). Total mortality is comprised of two components: 'natural' mortality (M);

mortality due to predation, disease, etc., and 'fisheries' mortality (F); mortality due to harvesting by humans, where

$$Z = M + F$$

The Exploitataion rate was obtained using the following equation (Gulland & Rosenberg, [1992](#)):

$$E = F/Z$$

RESULTS

## Length-weight relationship

The length and weight of *A. granosa* ranged between 11.25 and 33.13 mm and 3.04 and 15.55 g, respectively. The length-weight relationship of *A. granosa* displayed as $W = 0.002 L 2.328$ ($R^2 = 0.922$) which was found by plotting the length values against weight ([Figure 2](#)). The growth coefficient ($b$) was 2.328 ($\pm 0.08$). Therefore, the $b$ values ranged from 2.248 to 2.408 at 95% confidence level ([Table 1](#)). From this graph, the exponential form was turned into a linear form to obtain the length-weight relationship equation. The calculated equation for the length-weight relationship is $y = 2.328x - 2.537$, $R^2 = 0.922$ ([Figure 3](#)).
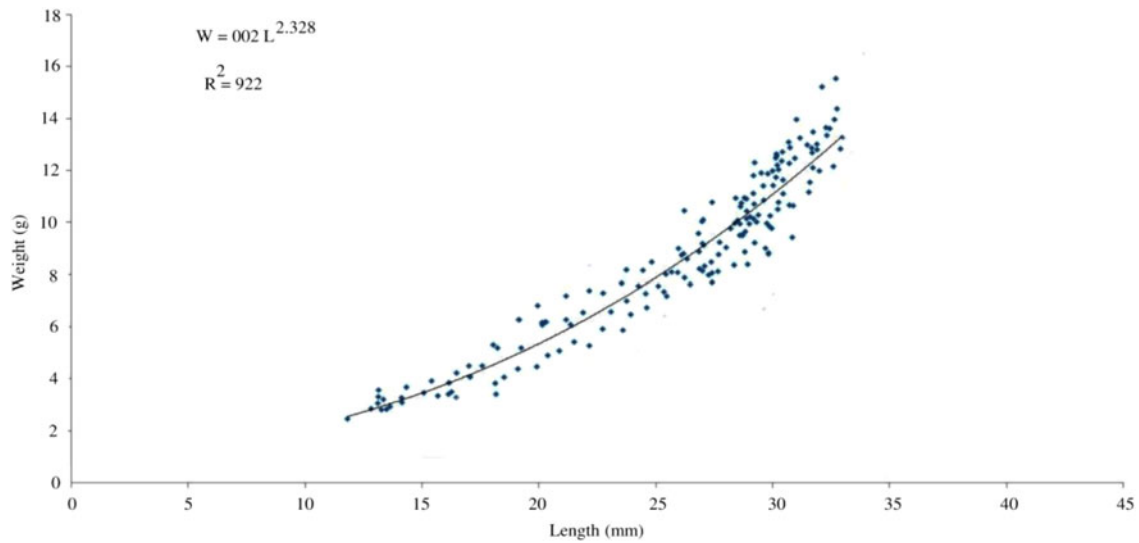
**Fig. 2.** Length-weight relationship of *Anadara granosa* from Balik Pulau, Penang Island, Malaysia.

**Table 1.** Descriptive statistics and estimated parameters of length-weight relationships of *Anadara granosa* in Balik Pulau, Penang Island, Malaysia (December 2011–November 2012).

| | $N$ | Total length (mm) | | Total weight (g) | | Regression parameter | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Max | $a$ | $b$ | CI 95% ($b$) | $r^2$ |
| *A. granosa* | 548 | 11.25 | 33.13 | 3.04 | 15.55 | 0.002 | 2.238 | 2.248–2.408 | 0.922 |

## Size frequency

A total of 548 specimens of *A. granosa* were collected on the monthly basis during this study. The size frequency of the shell length and number of *A. granosa* from Balik Pulau, Penang Island are shown in Figure 4. This figure shows that the shells in the population ranged from 11.25 to 33.13 mm. The majority of *A. granosa* were between 23.5 and 24.5 mm (48 individuals), while the lowest numbers of individuals (five) were between 11.5 and 12.5 mm.

## The growth parameters

The growth parameters ($L_\infty$, $K$, $t_o$) are useful in assessing the growth rates between and within individuals inhabiting various environments. The modified values for $K$ and $L_\infty$ for *A. granosa* were 1.1 year$^{-1}$ and 35.40 mm, respectively (Table 2).

The ideal fit index (Rn) for asymptotic length ($L_\infty$) and growth coefficient ($K$) was 0.371. Generally, the Rn value varies from 0 to 1 in the ELEFAN-FiSAT software. Since *A.*
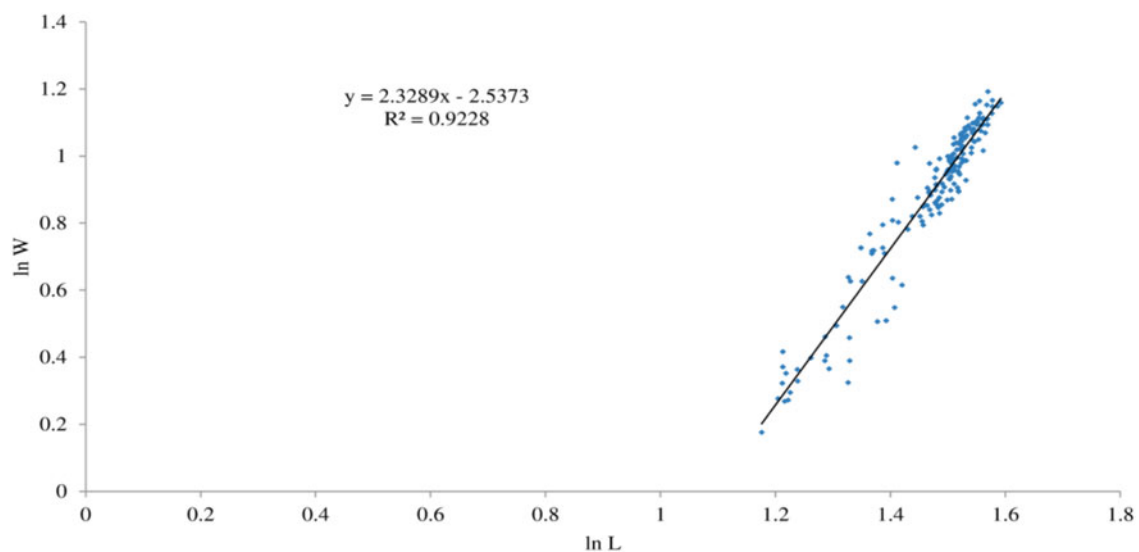


**Fig. 3.** The natural logarithms of length-weight relationship of *Anadara granosa* from Balik Pulau, Penang Island, Malaysia.
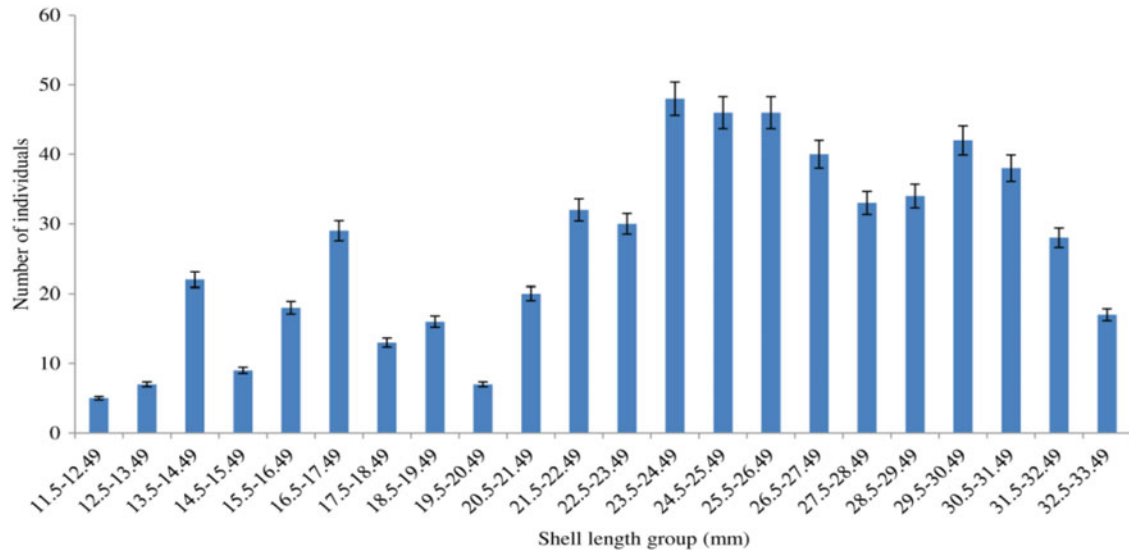
**Fig. 4.** Length-frequency distribution of samples of *Anadara granosa* collected from Balik Pulau, Penang Island, Malaysia.

**Table 2.** Estimated growth parameters of *Anadara granosa* in Balik Pulau, Penang Island, Malaysia (December 2011–November 2012).

| $L_\infty$ (mm) | $K$ (year$^{-1}$) | $t_o$ (month) | GPI (Ø) | Longevity (year) | $Z$ (year$^{-1}$) | $M$ (year$^{-1}$) | $F$ (year$^{-1}$) | $E$ |
|---|---|---|---|---|---|---|---|---|
| 35.40 | 1.1 | −0.140 | 3.13 | 2.72 | 3.02 | 1.84 | 0.48 | 0.20 |

*granosa* is a tropical species, the oscillation parameter ($C$) and winter point should be 0. The estimated $t_o$ value was −0.140 for *A. granosa* in Balik Pulau, Penang Island. The computed growth curve using these parameters is shown over the restructured length distribution in Figure 5.

## Von Bertalanffy growth model

The von Bertalanffy growth equation was $L_t = 35.40 [1 − EXP^{−1.1\ (t+0.140)}]$. It was found that the sizes attained by

*A. granosa* were 10.13, 14.36, 17.89, 20.82, 23.65 and 25.29 mm at the end of 2, 4, 6, 8, 10 and 12 months of age, respectively (Figure 6).

## Growth performance index

The growth performance (Ø′) was estimated at 3.13 using Pauly's method to compare growth patterns and evaluation of the reliability of the von Bertalanffy growth parameters.
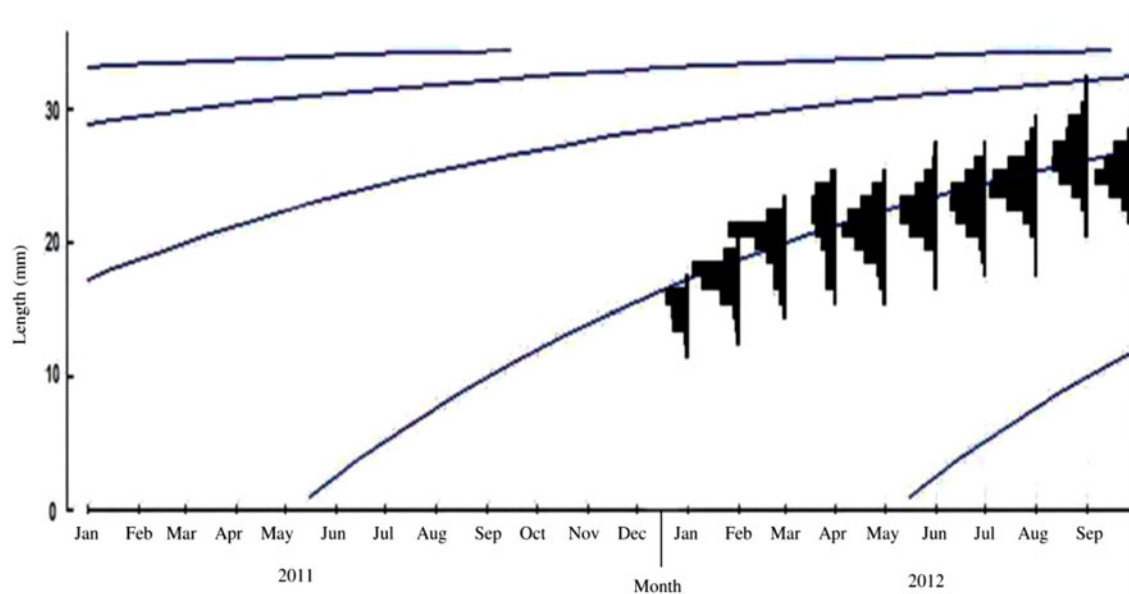


**Fig. 5.** Length-frequency distribution output from FiSAT with superimposed growth curves for *Anadara granosa* from Balik Pulau, Penang Island, Malaysia.
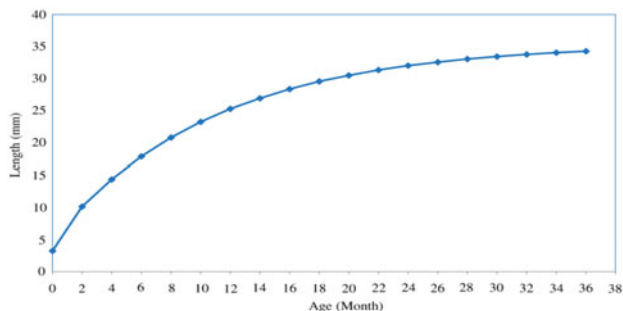
**Fig. 6.** The von Bertalanffy growth curve (plot of age and growth) of *Anadara granosa* based on computed growth parameters.

## Longevity

The longevity value for *A. granosa* was 2.72 years, which was obtained from Pauly's equation to identify the current state of fishery and manage cockle population exploitation. This value showed that *A. granosa* is a short-lived species.

## Mortality and exploitation

Length-converted catch curve was used to estimate the total mortality ($Z$) (Figure 7). The estimated total mortality ($Z$) of *A. granosa* was 2.32 year$^{-1}$. The natural mortality was estimated from the Pauly's equation. Therefore, the mean annual seawater temperature (28.8°C) was used in Pauly's equation to calculate the natural mortality in study site. Natural mortality ($M$) and fishing mortality ($F$) of *A. granosa* were 1.84 and 0.48 year$^{-1}$, respectively. The exploitation level ($E$) of *A. granosa* was 0.20 in study area.

## DISCUSSION

### Size frequency

The size of blood cockles may be summarized by shell length-frequency distributions, which is the size structure of the underlying populations (single species) or assemblages (multiple species). Recognizing the size structure of cockle populations is essential in understanding growth, reproduction, and
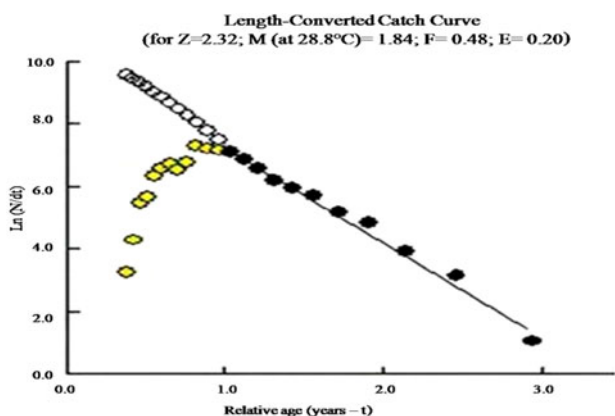


**Fig. 7.** Length-converted catch curve for *Anadara granosa* specimens collected from Balik Pulau, Penang Island from December 2011 to November 2012.

**Table 3.** The length range of blood cockles *Anadara granosa* derived by other authors in different study areas.

| Location | Length range of *Anadara granosa* | Source |
|---|---|---|
| Malaysia, Penang Island | 23.5 – 31.5 | Current study |
| Malaysia, Penang Island | 27.5 – 37.5 | Pathansali (1966) |
| Malaysia, Kuala Selangor | 30 – 41.23 | Broom (1985) |
| Malaysia, Kuala Juru | 21 – 31 | Oon (1980) |
| Malaysia, Kuala Sepetang | 25.5 – 30.5 | Oon (1980) |
| India, Kakinada Bay | 31.5 – 49.5 | Narasimham (1988a, b) |
| Australia, Blue Mud Bay | 38.46 – 41.23 | Faulkner (2009) |

recruitment, with changes in size an early indicator of disturbance. The present study was designed to determine the length-frequency distribution of *A. granosa* in Balik Pulau, Penang Island. Based on the length-frequency data, which followed a direct method of growth study, the size of blood cockles varied from 11.25 to 33.13 mm and the majority of shell lengths ranged from 23.5 to 31.5 mm, when the average size of cockle was between 23.5 and 24 mm. The results obtained in this study corroborated the findings of previous work in this field (Table 3). Pathansali (1966) reported that the length of *A. granosa* ranged from 27.5 to 37.5 mm in Penang Island, Malaysia. Furthermore, Oon (1980) reported that the size frequency distribution of *A. granosa* ranged from 21 to 31 mm (Kuala Juru, Pulau Pinang) and 25.5 to 30.5 mm (Kuala Sepetang, Perak). The similarity ranges between the findings of current study and those described by researchers in Malaysia, might be due to the location of the study areas.

However, the size frequency estimated by the current study was lower compared with the findings of Broom (1985) in Kuala Selangor, Malaysia (30.00 to 41.23 mm), Narasimham (1988a) in Kakinada Bay, India (31.50 to 49.50 mm) and Faulkner (2009) in Blue Mud Bay, Australia (38.46 to 41.23 mm). The disparity observed in the size frequency distribution might be due to the influence of latitude-dependent environmental factors. The *A. granosa* in this study site were also reared in a higher density per metre squared compared with natural mud flat beds in other studies. A possible explanation for this is that at a higher population density food supply decreases for each individual. Another explanation is that growth decreased at high densities due to reduction in space; this may lead to raised physical contact between cockles in the study area. Alternatively, it may be a genetic characteristic of the population occurring in the above-mentioned study areas. It is of interest to note that Muthiah *et al.* (1992) mentioned that the length-frequency distribution of *A. granosa* was higher under field culture in India compared with the growth observed in the culture fields in Malaysia.

### Length-weight relationship

In the field of biology, there are few correlations that are exactly linear; most of the bivariate correlations studied are non-linear. For example, the increase in live organism population size with time is exponential if there are no environmental stresses. The regression linear model cannot be used directly for variables with non-linear correlation (Ward, 2007). The direct usage of linear regression and the Pearson correlation was found to be inaccurate. Thus, one of the

**Table 4.** Length–weight relationship parameters (regression coefficient $b$, regression constant $a$) of *Anadara granosa* derived by other authors from different areas.

| Location | '$a$' value | '$b$' value | Source |
|---|---|---|---|
| Malaysia, Balik Pulau | 0.002 | 2.32 | Current study |
| Malaysia, Kuala Selangor | 0.24 | 3.37 | Broom (1982) |
| Malaysia, Sungei Buloh | 0.21 | 3.29 | Broom (1982) |
| India, Kakinada Bay | 0.26 | 2.12 | Narasimham (1988a, b) |
| Thailand | 0.36 | 3.04 | Boonruang & Janekarn (1983) |

approaches used to solve this problem is to use data embodiment to obtain a linear correlation between these two variables. The growth coefficient '$b$' may range from 2 to 4 (Koutrakis & Tsikliras, 2003). As mentioned earlier, linear regression analysis on the logarithm-transformed data showed the '$a$' (0.002) and '$b$' (2.328) parameters in the length-weight relationship. The '$b$' value (2.328) in the current study lay between the values mentioned by Koutrakis & Tsikliras (2003) and was significantly smaller than the isometric value ($b = 3$) at a 5% level. Therefore, the value of '$b$' in the current study demonstrates that *A. granosa* grows negative allometrically instead of isometrically. However, the results of this study were similar to the general study trend shown by Narasimham (1988b) in Kakinada Bay, India (2.12). Nevertheless, the '$b$' value of the current study had the smallest value compared with the findings of Broom (1982) in Kuala Selangor, Malaysia (3.37), Sungei Buloh, Malaysia (2.89) and Boonruang & Janekarn (1983) in Puket, Thailand (3.04) (Table 4). Several factors may influence the weight of soft tissue relative to shell length and can explain the differences in the current study. This might partly be explained through the influence of biological and ecological factors such as water temperature, density and shore level (Hickman, 1979). Furthermore, food availability can affect tissue growth, storage and utilization, which have the ability to change the ratio of total weight to shell length (Frechette *et al.*, 1992; Nakaoka, 1992).

In the current study, blood cockles of *A. granosa* were placed at an intertidal area in Balik Pulau, Penang Island. Therefore, differences of the growth rate of *A. granosa* compared with previous studies might be related to the time available for feeding and the available food supply during the immersion time in the intertidal area. The weight of soft tissue relative to shell length was lower at low elevation than high elevation. Differences in food density between the same species in different populations, or temporal variability in food availability may cause the different length-weight

relationship (McKinney *et al.*, 2004). Furthermore, changes in shell morphology due to phenotypic variation are also able to affect the weight of soft tissue relative to shell length between locations (Trussell, 2000).

## The age and growth parameters of *Anadara granosa*

The von Bertalanffy Growth Function (VBGF), a reliable explanation for growth rate of cockles (Caddy, 1989; Vakily, 1992), was examined in the present study for *A. granosa* and had a perfect fit for the length frequency data.

Yin *et al.* (2003) found that the growth curve in bivalves was sigmoid in shape and the von Bertalanffy growth model was able to provide an ideal fit in relation to length frequency. Furthermore, the sigmoid growth curves were observed in bivalves by Tsoularis & Wallace (2002) and Lei & Zhang (2004).

The growth parameters ($L_\infty$, $K$, $t_o$) are helpful in comparing the growth rates between and within species inhabiting different habitats. In the current study, an estimation of the von Bertalanffy parameters including asymptotic length ($L_\infty$) and growth coefficient ($K$) by ELEFAN I was 35.40 mm and 1.1 year$^{-1}$, respectively.

The growth parameters of *A. granosa* from this study showed differences from the results obtained in other studies (Table 5). The highest value of $L_\infty$ was 73.4 mm from Kakinada Bay, India (Narasimham, 1988b). In Malaysia, Oon (1980) reported the value of $L_\infty$ was 45.0 mm (Kuala Juru, Penang Island), 45.0 mm (Kuala Sepetang, Perak) and 41.4 mm (Sungai Besar Selangor). In addition, Broom (1982) showed the value of $L_\infty$ was 44.4 (Sungai Buloh) which was also slightly higher than the value found in this study. Differences between '$L_\infty$' may be due to differences in ecological characteristics of the culture plots, different stock density or size distribution that is associated with water depth. Based on this observation, the $L_\infty$ value of *A. granosa* from this study was similar to those results described by Vakily (1992) in Ang Sila, Thailand (36.89) and Oon (1980) in Pulau Sangga, Perak, Malaysia (37.4).

The $K$ value, which determines how fast the blood cockle *A. granosa* approaches its $L_\infty$ was a 'curvature parameter'. The $K$ value was very close to the findings of Broom (1982) in Malaysia, which showed the growth constant ($K$) was equal to 1.01 year$^{-1}$. Nevertheless, the growth constant ($K$) in the current study was higher compared with other research performed in Malaysia.

As *A. granosa* does not grow according to the von Bertalanffy growth equation during its whole lifespan, particularly in the juvenile stage, the curve often starts from the

**Table 5.** Estimated growth parameters of *Anadara granosa* derived by other authors in different areas

| Location | $L_\infty$ (mm) | $K$ (year$^{-1}$) | Growth performance (Ø) | $t_o$ | Source |
|---|---|---|---|---|---|
| Malaysia, Balik Pulau | 35.40 | 1.1 | 3.13 | −0.14 | Current study |
| India, Kakinada Bay | 73.4 | 0.58 | – | −0.4 | Narasimham (1988a) |
| Malaysia, Kuala Juru | 45.0 | 0.55 | 3.04 | 0.05 | Oon (1980) |
| Malaysia, Kuala Sepetang | 40.5 | 0.79 | 2.846 | −0.112 | Oon (1980) |
| Malaysia, S. Besar Selangor | 41.4 | 0.78 | 3.12 | 0.118 | Oon (1980) |
| Thailand, Ang Sila | 36.89 | 1.86 | 3.38 | – | Vakily (1992) |
| Malaysia, Pulau Sangga | 37.2 | 0.88 | 3.08 | 0.118 | Oon (1980) |
| Malaysia, Sungai Buloh | 44.4 | 1.01 | – | – | Broom (1982) |

negative side of the $x$-axis. Therefore, the theoretical age at zero length ($t_o$) often has a small negative value. The asymptotic age at zero length ($t_o$) of *A. granosa* for the current study was −0.14, which falls in the range of the initial condition parameters ($t_o$) of other studies. The value of this study was more than the value reported by Narasimham (1988a, b) at Kakinada Bay, India (−0.4) and was very close to the values reported by Oon (1980) in Malaysia (Table 4).

The growth performance index (φ) is a length-based index of growth that shows the interaction of growth constant ($K$) and asymptotic length ($L_\infty$). It was applied to give the potential growth rate of the blood cockle *A. granosa*. The φ was important for the evaluation of growth performance in similar species or between cockles of the same genus. There were similarities between the growth performance in this study (3.13) and those described by Oon (1980) at different areas in Malaysia and in the values of other studies. Therefore, it can be reasonably assumed that the growth constant ($K$) and asymptotic length ($L_\infty$) were an accurate representation of the blood cockle, *A. granosa* population in Balik Pulau, Penang Island that the estimations in the present study using the length-frequency distribution method are reliable.

Based on an estimation of age frequency from length frequency with the von Bertalanffy growth equation, the results of the present study indicated that *A. granosa* was 25.00, 32.03 and 34.28 mm on completion of 1, 2 and 3 years, respectively. The present results showed that the blood cockle, *A. granosa* from Balik Pulau, Penang Island has a lower growth rate compared with other studies. However, it seems possible that the low growth rate was due to a high density of *A. granosa* in the sampling site. Another possible factor that may affect the growth rate was the difference between elevations. Samples of *A. granosa* were located in the intertidal zone and immersed on average twice a day. Therefore, tidal fluctuations in salinity and turbidity at this site might have reduced the time available for feeding and access to food supplies. It is still important to consider that the growth in cockles was significantly affected by geographic and environmental parameters. Moreover, it has been found that there may be big changes in growth between the same species in different populations (Vakily, 1992; Stern-Pirlot & Wolff, 2006). A variety of environmental factors such as the immersion period, turbidity, seawater temperature (Broom, 1982), salinity (Ivanovici et al., 1981; Broom, 1982) and water pollution (Din & Ahamad, 1995) have been confirmed to influence the growth rate of different *Anadara* spp. populations.

## Longevity and mortality

The estimated longevity or maximum age value was 2.72 years for the blood cockle *A. granosa* in Balik Pulau, Penang Island,

Malaysia. The present findings seem to be consistent with Narasimham (1969) in Kakinada Bay, India (3 years) which showed *A. granosa* is short-lived.

Mortality is an important parameter to understanding the dynamic population of cockles. The total mortality ($Z$), natural mortality ($M$) and fishing mortality ($F$) using the length-transformed catch curve was 2.32, 1.84 and 0.48 year$^{-1}$, respectively (Table 6). Due to the experimental design in the preparatory step, the data for mortality study was obtained from individuals that were in an enclosure transplant area. As a result, mortality that occurred in the study site was considered to be from natural causes ($M$). There were little empty shells and dead samples in the study site, which could be the reason for the existence of natural mortality. In addition, the results of the theoretical calculation of total mortality in the current study showed that the fishing mortality level was very low and may be explained by the direct removal of animals (monthly sample collection) as fishing mortality in the study area.

Based on Al-Barwani et al. (2007), total mortality included natural and fishing mortality ($Z = M + F$). The yield was ideal when $F = M$. Therefore, in the current study, higher natural mortality compared with fishing mortality indicated the unbalanced position of the cockle population.

The exploitation rate ($E$) was estimated with the value of fishing mortality divided by the value of total mortality ($E = F/Z$). When E was more than 0.5, the stock was over-fished (Gulland, 1965). However, the findings of this study confirmed the unbalanced condition in the stock and the lower value of $E$ (0.20) indicated the 'under-fishing' condition (under-exploitation) of *A. granosa* which led to a decrease in biomass in the study area.

With this information, the management authorities can monitor the growth of the cockles and monitor the proper size for harvesting as well as for population growth. Further research regarding the stock assessment should take into account the marked differences in growth parameters of cockle populations. Furthermore, due to its economic importance, we recommend that future management should include better protection for *A. granosa* and a monitoring system should be initiated in order to collect size composition data for different fishing areas.

Table 6. Estimated mortality parameters of *Anadara granosa* in Balik Pulau, Penang Island, Malaysia.

| Location | $Z$ (year$^{-1}$) | $M$ (year$^{-1}$) | $F$ ($Z - M$) (year$^{-1}$) | $E$ ($F/Z$) |
|---|---|---|---|---|
| Balik Pulau, Penang Island | 2.32 | 1.84 | 0.48 | 0.206 |

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