

Variation in Physiological Energetics of the Ark Shell *Scapharca broughtonii* (Bivalvia: Arcidae) from Gamak Bay, South Coast of Korea

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This study presents physiological rates of respiration and excretion, clearance rate, and assimilation efficiency of the ark shell *Scapharca broughtonii*, determined during 2007 from specimens collected in Gamak Bay on the south coast of Korea. Physiological parameters were measured monthly under static, laboratory controlled conditions with ambient conditions, and measurements were performed seasonally in order to estimate scope for growth and its probable sources of variation. Temperature directly influenced respiration and excretion. Clearance rates showed a tendency to be low during May-August, which is a period of gametogenesis. Assimilation efficiency was not significantly different seasonally and was independent of the concentration of chlorophyll a. The scope for growth was negative during high-temperature months (July–August), reflecting the high temperature and low clearance rate, and had its highest positive values during spring and autumn. The energy budget or growth potential of bivalves has been applied to other economically important species. Data on the physiological parameters and scope for growth of *S. broughtonii* obtained in this study will be used to assess the carrying capacity for ark shell cultivation.

Key words: *Scapharca broughtonii*, Physiological parameters, SFG

Introduction

Physiological responses can be used to provide an assessment of individual health because they represent non-specific responses to the sum of environmental stimuli, and therefore complement more specific responses at the biochemical level. They are also capable of reflecting environmental deterioration before such effects manifest themselves in the population or community. The primary requisite for the survival of any organism is the maintenance of a positive energy balance, which is directly linked to the quality of the environment (Smaal and Widdows, 1994). Energy balance can be estimated by the difference between the energy acquired from available food and the energy consumed by internal metabolism (Parsons et al., 1984; Dame 1996). When positive, this energy balance, defined as the scope for growth, represents the energy available for growth (somatic tissue)

and/or reproduction (gonadal maturation).

Temperature is the most important exogenous factor regulating the metabolism of exothermic organisms, and its influence on the rates of oxygen consumption, feeding, and nitrogen excretion in temperate species of marine bivalves has been studied extensively (Newell and Branch, 1980; Bayne and Newell, 1983). These studies show that the rates of physiological functions are positively correlated with seasonal variations in temperature (Newell and Branch, 1980; Bayne and Newell, 1983). Superimposed on the seasonal metabolic cycles associated with temperature are variations related to endogenous factors such as nutritional and reproductive condition (Huang and Newell, 2002). Although the metabolic rate of mussels (Hilbish, 1987; Huang and Newell, 2002) and oysters (Mao et al., 2006) at different temperatures have been determined, scarce information appears to be available on the ark shell *Scapharca broughtonii*. Most studies on *S. broughtonii* have concentrated on its culture (Min et al., 2004; Kim et al., 2007), and only a few have

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examined its physiology (Shin et al., 2002, 2006). The ark shell belongs to the family Arcidae and is distributed in countries with latitudes similar to those of South Korea, including Japan and China, where the species is cultivated commercially. *S. broughtonii* (Fig. 1) has hemoglobin in its blood as a respiratory pigment, and it has been known as a health food in South Korea. The production of this clam in South Korea peaked in 1998. Yields have decreased gradually since 1998, with a current annual survival rate of 3-5%, necessitating urgent efforts to examine the causes of death and the decrease in the productivity of this mollusk. This work presents the physiological rates and scope for growth (SFG) of the ark shell in Gamak Bay, Korea, and seeks to explain its variations based on laboratory experiments. This study provides basic data for assessing the ark shell carrying capacity of culture farms in Gamak Bay on the south coast of Korea.



Fig. 1. External morphology of *Scapharca broughtonii*.

Materials and Methods

Sampling Area

The present experiment was conducted in Gamak Bay (Fig. 2), Korea, from January to December 2007. The average depth of the culture area was 6 m (maximum 10 m). The sampling site is located at the edge of Gamak Bay, and when it rains, fresh water flows into the area.

Sampling and Biological Measurements

From January 2007 to December 2007, 80 animals were collected monthly from Gamak Bay. The wet weight (WW, g) and shell length (L, mm) of 30 ark shells were measured to establish the relationship between WW and L expressed as $WW = a \times L^b$ (a and b are constants) in each month. The condition index (CI) of ark shells was determined according to Crosby and Gale (1990) by the formula:

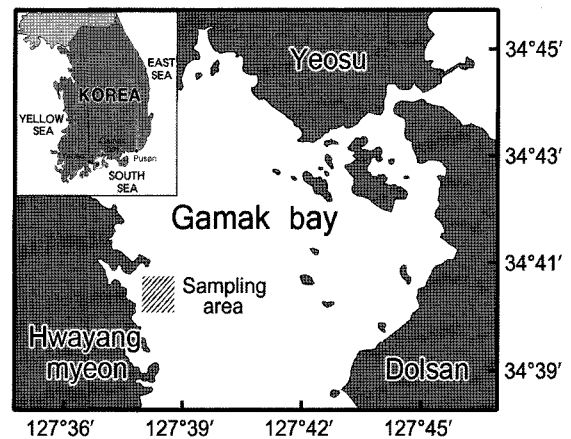


Fig. 2. *Scapharca broughtonii* sampling site.

$$CI = \frac{\text{Dry weight}}{\text{Total weight} - \text{Shell weight}} \times 100$$

Fifty ark shells (shell length, 8.2-12.5 cm) were selected and acclimated for 3 days under ambient seawater conditions in the laboratory for physiological experiments. After physiological measurements were completed, the soft tissue from each ark shell was excised, weighed, and then dried at 80°C for 24 hrs to a constant weight.

Physiological Parameter Measurement

The respiration rate (oxygen consumption rate, RR) and ammonium excretion rate (ER) of ark shells were measured in a closed, 2.0 L volume respiratory chamber. Two or three ark shells, depending on their size, were placed into a chamber, which was placed in a large water tank to maintain constant ambient water temperature, and the experiments were repeated 10 times. Three chambers without ark shells were used as controls in each run. After 2 or 3 hours, the chambers were taken out of the large water tank, ark shells were removed, and water samples from every chamber were taken immediately. At the end of the experiment, the water volume of each chamber (excluding the ark shell volume) was measured. Oxygen concentrations were determined using an oxygen meter (Orbis, 3600 made by Switzerland). Ammonium measurements were taken simultaneously with those of oxygen consumption. A 2 mL water sample was siphoned from each respiration chamber when the chambers were removed from the seawater. Ammonium analyses were carried out according to the phenolphthoride methodology (Solórzano, 1969).

Clearance rate (CR) was estimated by measuring the removal of suspended particles from water

flowing through the chambers containing ark shell individuals. Mixtures of *Isochrysis galbana*, *Tetraselmis* sp. and *Chaetoceros* sp. were supplied as feed for clearance rate experiments. A coulter counter fitted with a 100 μm -orifice tube was used to determine the difference between the particle concentration in the outflow from the control chamber (C_1) and the outflow from each experimental chamber containing an ark shell (C_2). CR was calculated as follows.

$$\text{Clearance rate (L h}^{-1}\text{)} = \left[\frac{C_1 - C_2}{C_0} \right] \times \text{flow rate (Lh}^{-1}\text{)}$$

(Hildreth and Crisp, 1976).

Experiments to estimate absorption efficiency (AE) were carried out under the same conditions as the tests for feeding rates, but with durations of 24 hrs. The estimate proposed by Conover (1966) consists of comparing the content of organic matter present in the phytoplankton offered with the content of organic material in the feces produced. The estimates were made according to the equation:

$$\text{AE} = \left[\frac{(I-F)}{(I-F) \times I} \right] \times 100$$

where

AE: Absorption efficiency (%)

I: Percentage of organic matter in the food offered (phytoplankton)

F: Percentage of organic matter in feces.

The scope for growth was calculated monthly using the factors of energy conversion presented by Bayne et al. (1985):

1 mg organic matter = 23.50 J

1 mL O_2 respired = 20.33 J

1 μg $\text{NH}_4\text{-N}$ excreted = 0.0249 J.

And the estimated scope for growth was measured in joules using the equation

$$\text{SFG} = \text{A} - [\text{R} + \text{U}]$$

SFG: Scope for growth ($\text{J h}^{-1} \text{g}^{-1}$)

A: Energy absorbed

R: Respiration rate

U: Excretion rate

Data Analysis

The relationships between shell length (SL) and wet weight (WW) were modeled as $\text{WW} = a \times \text{L}^b$. All statistical analyses were ANOVAs, executed using SPSS.

Results

Environment of the Sampling Site

The average temperature range was 7–12°C in winter and 20–25°C in summer. Salinity varied slightly from 30.1 psu to 33.8 psu, with the minimum in May due to rainfall. Mean chlorophyll a concentration was 4.6 $\mu\text{g L}^{-1}$, with a maximum of 13.04 $\mu\text{g L}^{-1}$ in September (Fig. 3).

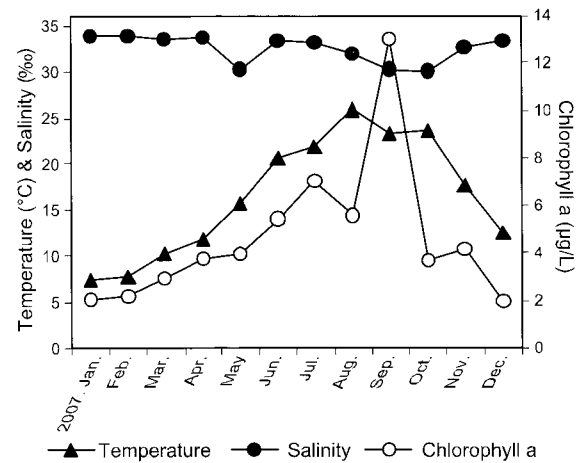


Fig. 3. Monthly variation of water temperature, salinity and chlorophyll a in Gamak bay.

Seasonal Allometry of Length and Weight in *S. broughtonii*

The seasonal regression of wet weight against shell length for *Scapharca broughtonii* is summarized in Table 1. The b values ranged between 2.0428 in December and 3.3981 in October. Different b values indicate the physiological conditions and growth characters in different months. Low b values, which indicate increased energy expenditure and substance storage, were identified in December under low levels of chlorophyll a, and in August before, during, and after spawning. The highest b values, indicating increased growth rate, were observed in May and October.

Respiration Rate (Oxygen Consumption, RR)

Fig. 4 shows the monthly variation in the oxygen consumption rate ($\text{mgO}_2\text{h}^{-1}\text{g}^{-1}$) of ark shells. RR increased from February and reached a peak in August with a mean of $0.2 \text{ mgO}_2\text{h}^{-1}\text{g}^{-1}$, followed by a rapid decline to a minimum in November, with the lowest value of $0.071 \text{ mgO}_2\text{h}^{-1}\text{g}^{-1}$, similar to the values recorded in winter from October to January. Maximum RR matched the highest temperature in August, acclimating with ambient temperature.

Table 1. Regression coefficients of wet weight (WW, g) and shell length (L, cm) in *Scapharca broughtonii* (expressed as $WW=a \times L^b$) from Gamak bay

Month	WW(g)	L(Cm)	r ²	n	A	b	F
Jan. 2007	37.5- 68.7	6.9- 9.5	0.7253	30	0.6468	2.1226	73.365*
February	38.2- 72.8	7.1- 8.8	0.7908	30	0.1998	2.7377	117.123*
March	16.1- 58.6	5.0- 8.3	0.8764	30	0.2047	2.7189	198.001*
April	38.6-105.7	6.9-10.3	0.7451	30	0.3038	2.464	81.136*
May	15.4- 66.6	6.1- 8.5	0.9057	30	0.0502	3.3313	270.754*
June	30.7- 65.9	6.5- 8.6	0.8103	30	0.1691	2.7718	119.633*
July	19.8- 40.9	5.8- 7.6	0.7979	30	0.2382	2.487	110.564*
August	19.9- 32.2	5.8- 7.2	0.5684	30	0.5041	2.0805	154.859*
September	17.4- 40.6	5.7- 7.9	0.7087	30	0.1951	2.5534	68.126*
October	18.1- 39.7	6.5- 8.0	0.8469	30	0.0333	3.3981	36.881*
November	25.3- 47.7	6.4- 7.9	0.8009	30	0.3935	2.3222	36.881*
December	13.6- 24.5	4.9- 6.0	0.5684	30	0.5904	2.0428	55.089*

* $p < 0.05$.

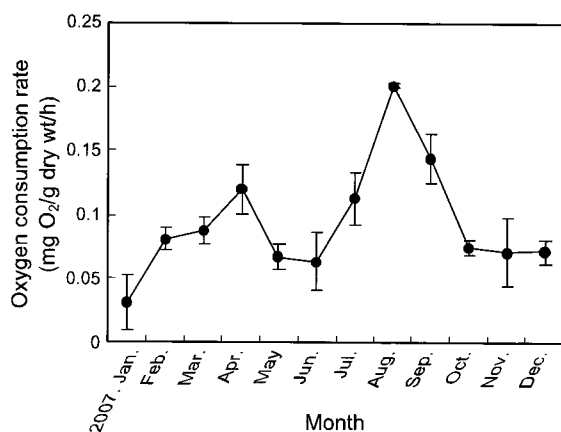


Fig. 4. Monthly variation of oxygen consumption rate in *Scapharca broughtonii* from Gamak bay. Values are means \pm SD.

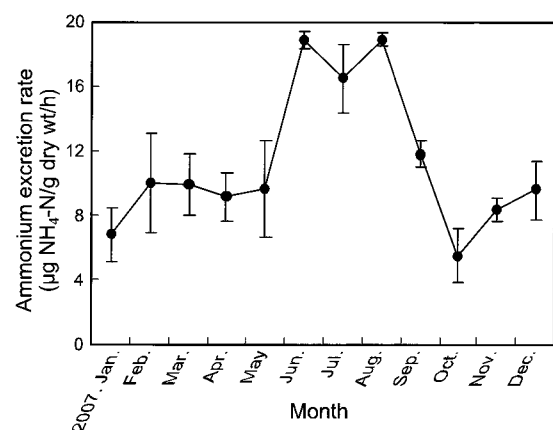


Fig. 5. Monthly variation of excretion rate in *Scapharca broughtonii* from Gamak bay. Values are means \pm SD.

Ammonium Excretion Rate (ER)

Fig. 5 shows monthly variation in the ammonium excretion rate. The ammonium excretion rate of ark shells varied significantly with season. Ark shell ER was high from June to August ($16.5-18.9 \mu\text{g NH}_4\text{-N g}^{-1}\text{h}^{-1}$) and then declined from September to January, reaching its lowest value in January ($6.8 \mu\text{g NH}_4\text{-N g}^{-1}\text{h}^{-1}$). Ark shells excreted the least ammonium under the lowest temperatures in winter and the most ammonium under the highest temperatures in summer.

Clearance Rate (CR)

The clearance rates of ark shells in the chambers varied monthly (Fig. 6). CR began to increase from March, abruptly declined from May to August, and then peaked in September ($1.1 \text{ L}^{-1} \text{ gDW}^{-1}\text{h}^{-1}$) with maximum chlorophyll a. The low clearance rate of ark shells was highlighted in winter (average $0.52 \text{ L}^{-1} \text{ gDW}^{-1}\text{h}^{-1}$) and during the spawning season from June to August (average $0.44 \text{ L}^{-1} \text{ gDW}^{-1}\text{h}^{-1}$).

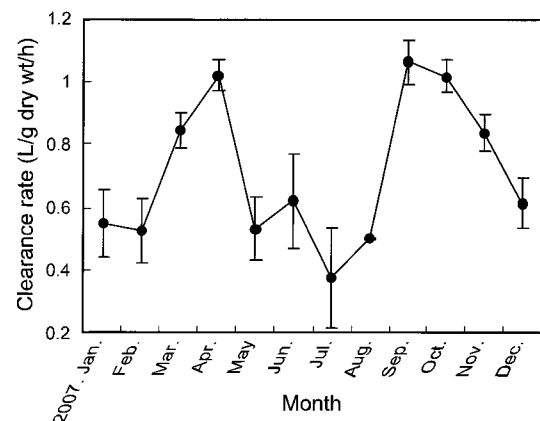


Fig. 6. Monthly variation of clearance rate in *Scapharca broughtonii* from Gamak bay. Values are means \pm SD.

Assimilation Efficiency (AE)

Fig. 7 shows changes in the monthly assimilation efficiency of ark shells, which ranged from 68.4% to

Table 2. Scope for growth of *Scapharca broughtonii* from Gamak bay

Month	CR (L/h)	POM ×23.5 (mg/L) (J/mg)	Energy consumed (C) (J/h)	AE (%)	Energy absorbed (A) (J/h)	R (J)	U (J)	SFG (J/h)
January/February	0.53 ± 0.001	× 5.08	2.69 ± 0.08	78.6 ± 6.36	2.09 ± 0.08	0.92 ± 0.32	0.21 ± 0.05	0.96
March/April	0.93 ± 0.01	× 5.08	4.72 ± 0.37	79.2 ± 2.68	3.72 ± 0.37	1.48 ± 0.32	0.24 ± 0.01	2
May/June	0.57 ± 0.04	× 5.08	2.90 ± 0.35	76.1 ± 3.74	2.20 ± 0.35	0.93 ± 0.03	0.35 ± 0.16	0.95
July/August	0.44 ± 0.11	× 5.08	2.24 ± 0.25	70.1 ± 2.33	1.57 ± 0.25	2.23 ± 0.88	0.38 ± 0.11	-1.04
September/October	1.03 ± 0.01	× 5.08	5.23 ± 0.08	72.7 ± 0.71	3.77 ± 0.08	1.55 ± 0.69	0.22 ± 0.11	2.06
November/December	0.72 ± 0.02	× 5.08	3.66 ± 0.52	72.3 ± 1.27	2.63 ± 0.52	1.02 ± 0.01	0.22 ± 0.02	1.39

Note: C=CR (L/h)×POM (mg/L)×energy content of POM (J/mg) (Widdows et al., 1981); A, Energy absorbed (J/h); SFG=A-(R+U).

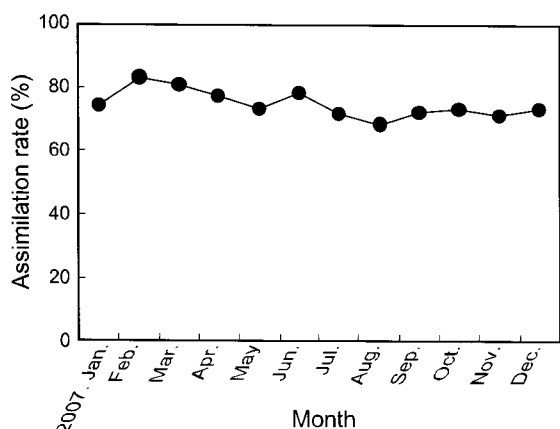


Fig. 7. Monthly variation of assimilation rate in *Scapharca broughtonii* from Gamak bay.

83.1%. Analysis of variance (ANOVA) showed no significant seasonality in ark shell assimilation efficiency except during August, with 68.4% ($P>0.05$).

Scope for Growth (SFG)

The scope for growth exhibited marked seasonality in the cultivation area of Gamak Bay in Yeosu (Table 2), with a minimum value in July and August ($-1.04 \text{ Jg}^{-1}\text{h}^{-1}$) due to the high respiration rates and low clearance rates, and a maximum value in September and October ($2.06 \text{ Jg}^{-1}\text{h}^{-1}$) due to high clearance rates. SFG variation was not related to variations in chlorophyll a concentrations in the area.

Discussion

Temperature and salinity are important physical factors that affect the lives of marine organisms and ultimately determine their geographical distributions (Kinne, 1966). According to Shin et al. (2006), salinity at intervals between 26.4 and 33.0 psu under acclimatized laboratory conditions has little influence on the rates of physiological processes in ark shells *Scapharca broughtonii*. According to results obtained in the present study, average rates did not show any

correlation with salinity, presumably because the salinity of the environment was within this tolerance interval, even though salinity was slightly reduced in May (30.1 psu).

Temperature has a strong influence on respiration rates, and an organism is unable to compensate for this influence (Resgalla et al., 2006). Energy expenditure of mussels has been observed to be strongly influenced by high temperatures (Hicks and McMahon 2002). Furthermore, various authors have highlighted the fact that respiration rates are related to the reproductive cycle of bivalves, particularly to gametogenesis (Bayne et al., 1976; Bayne and Widdows, 1978; Widdows, 1978).

Numerous studies have also examined oxygen consumption rates in bivalves. For example, oxygen consumption rates were $0.22\text{-}0.33 \text{ mL O}_2\text{gDW}^{-1}\text{h}^{-1}$ for scallops *Placopecten magellanicus* (MacDonald et al., 1998), $0.11\text{-}0.33 \text{ mL O}_2\text{gDW}^{-1}\text{h}^{-1}$ for clams *Mya arenaria* (MacDonald et al., 1998), and $1.72 \text{ mg O}_2\text{gDW}^{-1}\text{h}^{-1}$ in summer for oysters *Crassostrea gigas* (Mao et al., 2006). *Perna perna* (Resgalla et al., 2006) exhibits higher respiration rates in periods after the liberation of gametes. The highest value of oxygen consumption in our study was $0.201 \text{ mg O}_2\text{gDW}^{-1}\text{h}^{-1}$ in August (average temperature 25.9°C). This coincides with the period during which water temperature was the highest and which precedes and follows the spawning of ark shells.

Although the main spawning season of ark shells has not been fully confirmed, floating ark shell hatchlings distributed throughout Chinhae Bay in Korea have been reported to appear from July to October (Yoo et al., 1988), whereas the maturation of gonads and the spawning of gametes of D-type hatchlings appears from the end of July (Yoo et al., 1988), probably indicating that gonadal maturation begins in June. In accordance with such reports, the respiration rate of ark shells is dependent on temperature acclimatization, which is high during the spawning season. As such, it appears that much

energy is consumed due to the high respiration rate.

To date, no studies have reported on ammonium excretion from ark shells, although according to Huang and Newell (2002), the ammonium excretion rate of *Gerkenia demissa* showed a similar seasonal pattern to that detected in the present study; $9.56 \mu\text{g NH}_4\text{-Ng DW}^{-1}\text{h}^{-1}$ in spring, 18.1 in summer, and 8.26 in winter. In our study, the highest recorded rate of ammonium excretion ($18.9 \mu\text{g NH}_4\text{-NgDW}^{-1}\text{h}^{-1}$) was in August (spawning season), indicating excess utilization of protein during this period. The ammonium excretion rate was lowest during winter.

The parameter that most influences the clearance rates of bivalves is the quantity and quality of available food, as demonstrated for *Perna viridis* (Wong and Cheung, 2001) and *Mytilus edulis* (Bayne and Newell, 1983). Bivalve filter feeders are capable of exhibiting great plasticity in their feeding responses to optimize their energy gain from the environment. The results obtained in this work demonstrate that feeding rates are not correlated to the amount of available food (Figs. 3 and 6).

The clearance rate was reduced from May to August, which overlaps with the spawning season of ark shells in the studied site. It is difficult to find reports that show clear decreases in the feeding rates of shellfish during their reproductive season. However, *Argopecten purpuratus* (Navarro et al., 2000) is able to actively control its clearance rate in accordance with feeding composition during gametogenesis. It has been concluded that this is due to the ability of *Argopecten purpuratus* to recognize specific nutritive compounds within its feed due to the presence of chemical receptors in its gill and labial palps (Ward et al., 1992; Navarro et al., 2000). The low ark shell feeding rate during gametogenesis found in this study appears to be caused by differences in feed composition between the experimental environment and the ark shells' natural habitat. As such, more detailed research on the relationship between clearance rate and gametogenesis is required.

Assimilation efficiency has been described as a physiological process significantly affected by quality and quantity of diet (Bayne and Newell, 1983).

The annual average assimilation efficiency of ark shells in this study was 74.8% without significant annual differences. The fact that no change in assimilation efficiency was observed despite a period of reduced clearance rate appears to be due to the fact that diatoms such as *Isochrysis galbana* and *Chaetoceros* sp., which were provided as feed, can be easily digested (Epifanio, 1983; Laing et al., 1987).

The scope for growth is a direct reflection of the

effect of the quality of the environment on the maintenance of positive energy balance of organisms, and consequently, their survival, growth and reproduction (Gabbott, 1982; Dame, 1996). Various factors influence this energy balance, but the principal influences are temperature and the availability and quality of food (Bayne and Newell, 1983; Griffith and Griffith, 1987). In this study, the scope for growth was dependent on energy expenditure (oxygen consumption rate) and the inhibition of feeding rate, which was related to the reproductive cycle (spawning season) of ark shells during the summer months. The negative SFG was the result of reduced feeding rates between July and August, whereas higher SFG values were the result of increased feeding and reduced respiration during spring and autumn.

An increase in expended energy as reflected in metabolic activity was observed due to the capacity of this species to show thermal compensation in physiological rates during periods of elevated temperature. Therefore, it seems that negative SFGs were induced by the consumption of energy-containing materials to compensate for physiological temperature during the spawning period and periods of elevated water temperature. The seasonality observed in the SFG variations was compared with the average values of the condition index of the ark shells. Condition index is a frequently used parameter in mariculture, as it shows the quality of the organism in commercial terms and also suggests its nutritional status in terms of growth and maturity, which in turn, is influenced by environmental conditions (Lucas and Beninger, 1985; Dame, 1996). A strong correlation was observed between CFG and CI (Fig. 8), demonstrating that the energy balance of ark shells results from the sum total of the somatic and reproductive

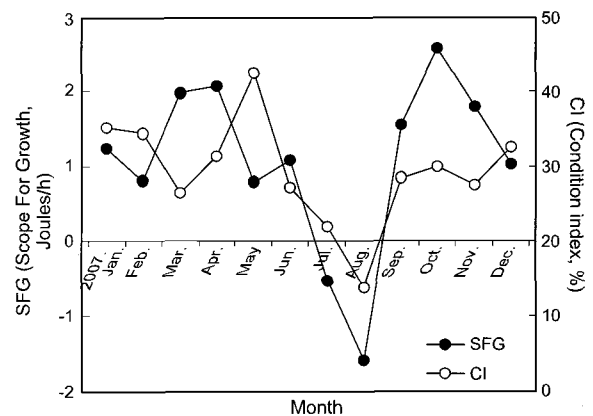


Fig. 8. Monthly variation of SFG and CI in *Scapharca broughtonii* from Gamak bay.

growth rates, which is the definition of the scope for growth. The possibility of this relationship was stressed by Resgalla et al. (2007).

It has been reported that physiological rates of energy acquisition are not relevant to somatic growth rate (Iglesias et al., 1996). Therefore, it appears that the increased consumption of energy-containing materials is related to somatic growth and can perform as an indicator of organism health.

Acknowledgements

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