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Production of *Acartia steueri* (Copepoda: Calanoida) in Ilkwang Bay, Southeastern Coast of Korea

HYUNG-KU KANG* and YONG JOO KANG

Department of Marine Biology, Pukyong National University, Nam-gu, Busan 608-737, Korea

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Production of the marine calanoid copepod *Acartia steueri* was measured from 2 October 1991 to 8 October 1992 at a station in Ilkwang Bay, on the southeastern coast of Korea. Phytoplankton standing stock ranged over 1.0 to 9.3 mg chl.*a* m^{-3}, and annual primary productivity (by the C-14 method) at three stations was estimated at 200 gC m^{-2}yr^{-1}. *Acartia steueri* (nauplii + copepodids + adults) were present in the plankton throughout the year, with seasonal variation in abundance. Biomass of *A. steueri*, excluding the NI stage, was 0.01–4.55 mgC m^{-3} (mean: 0.68 mgC m^{-3}) with peaks in November, February, May and July–early August, and relatively low biomass in September–January. Instantaneous growth rates of the nauplius stages were higher than the copepodid stages. Annual production of *A. steueri* was 25.1 mgC m^{-3}yr^{-1} (or 166 mgC m^{-2}yr^{-1}), showing peaks in November, May and July–August with a small peak in February, and low production in December–April and September–October. There were no significant relationships between the daily production rate of *A. steueri* and temperature or chlorophyll *a* concentration, indicating that unknown other factors might be related to the variation of the production rate.

Keywords:
· Copepod,
· *Acartia steueri*,
· biomass,
· production,
· temperature,
· chlorophyll *a* concentration.

1. Introduction

Estimation of zooplankton production is a primary goal of zooplankton research in relation to the GLOBEC program (IGBP, 1999). While copepods are the major constituents of zooplankton in Korean waters (Shim and Lee, 1986; Park *et al.*, 1991; Hwang and Choi, 1993; Kim *et al.*, 1993; Myung *et al.*, 1994; Go *et al.*, 1996; Kang and Kim, 2002), as they are in most marine waters around the world, little information on copepod production is available here. To better understand the structure and functioning of marine ecosystems, it is very important to measure the variations of biomass and production of major trophic levels and to predict the major forcing factors controlling the variations (IGBP, 1999).

Acartia steueri is a small pelagic marine copepod that is distributed in the coastal area of the northwestern Pacific Ecosystem (Uye, 1980, 1981; Kim, 1985; Yoo *et al.*, 1991; Go *et al.*, 1994). In general, *Acartia omorii* is known as one of the dominant copepods in coastal waters of Korea (Kang and Kim, 2002). However, the abundance of *A. steueri* seems to have been underestimated in Korean waters, because *A. steueri* has often been identified as *A. omorii*. There is little data on the production and population dynamics of *A. steueri*, except for the growth and egg production from Uye (1980, 1981).

The purposes of this study was therefore to measure the production rate of *A. steueri* in Ilkwang Bay, and to understand the potential factors including temperature, chlorophyll *a* concentration and primary productivity of phytoplankton that might control its production here.

2. Methods

A series of samples were collected at a station (St. 3) in Ilkwang Bay on the southeastern coast of Korea from 2 October 1991 to 8 October 1992 (Fig. 1). Zooplankton samples were taken by oblique hauls from the bottom to the surface using a plankton net (31 cm mouth diameter, 64 μm mesh), and were fixed with 5% neutralized formalin solution. The copepod *A. steueri* from whole samples or split sub-samples was enumerated and stage-identified.

Water temperature, salinity, chlorophyll *a* concentration and primary productivity were monitored during the sampling period. Water temperature was measured using a thermometer in the field at surface and bottom water, and salinity was measured from surface and bottom water using a salinometer in the laboratory. Chloro-

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* Corresponding author. E-mail: kanghk@kordi.re.kr

Present address: Marine Living Resources Research Division, Korea Ocean Research & Development Institute, Ansan P.O. Box 29, Seoul 425-600, Korea.

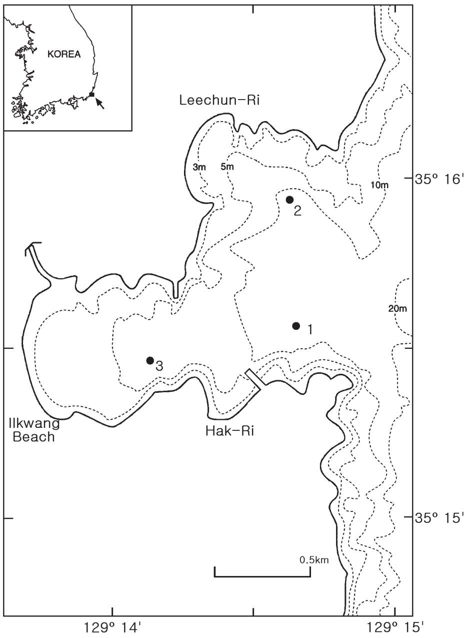

Fig. 1. Study area showing location of sampling stations in Ilkwang Bay.

phyll *a* concentration was measured by the spectrophotometric method (Parsons *et al.*, 1984) from surface and bottom water (750–1000 mL) filtered onto membrane filter (0.45 pore size, Whatman). Primary productivity of phytoplankton was measured by the C-14 method (Parsons *et al.*, 1984) at three stations (Fig. 1). Water samples from middle depth at each station were introduced into B.O.B bottle (250 mL) with inoculation of *ca.* 0.5 μCi mL^{-1} of sodium C-14 bicarbonate (Amersham) as working solution. The incubation bottles were incubated *in situ* on deck at different light intensities (100, 66, 35, 21 and 1–2% of incident light) for 1.5–2.5 hrs. Incubations were terminated by filteration of samples on GF/C glass fiber filter (Whatman). After acid-fuming of filtered samples to remove the inorganic C-14 absorbed in the filter, Scint-A (Packard) was used as liquid scintillation cocktail, and C-14 activity of the working solution and quenching of samples were determined by liquid scintillation counter (Packard Tricarb 4530).

Population production rate (P, μgC m^{-3}day^{-1}) of *A. steueri* was calculated using the growth rate method (Hutchings *et al.*, 1995; Liang and Uye, 1996a; Liang *et al.*, 1996):

$$P = \sum_{i=NII}^{CV} \left(B_i \times g_i\right) + B_f \times g_f$$

where, B_i and B_f are biomass (μgC m^{-3}) of stage i and adult females, respectively. g_i is the instantaneous growth rate (day^{-1}) of stage i. g_f is the specific egg production rate (day^{-1}) of adult female. We assumed that the production by naupliar stage N1 and adult male was negligible.

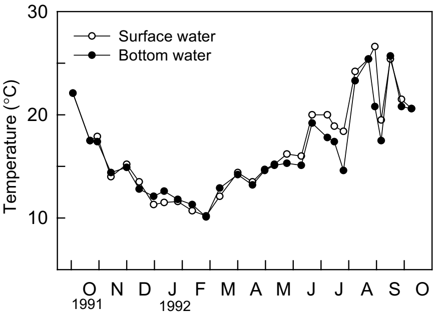

Fig. 2. Seasonal variation in water temperature at St. 3.

Total length of nauplii and prosome length of copepodids and adults of *A. steueri* from split sub-samples were measured to the nearest 10 μm under a microscope fitted with an eye-piece micrometer for >30 specimens. The carbon content (W, μg) of an individual of *A. steueri* was estimated from the length-weight relationship of Kang and Kang (1997) for copepodids and adults:

$$\mathrm{LogW} = -8.508 + 3.106\mathrm{LogPL}$$

and for nauplii:

$$\mathrm{LogW} = -4.188 + 1.451\mathrm{LogTL}$$

where, PL is prosome length (μm) and TL is total length (μm).

The specific egg production rate of adult female was estimated by substituting ambient water temperature (T, °C) and chlorophyll *a* concentration (S, mg chl.*a* m^{-3}) into the equation of Kang and Kang (1998a):

$$g_f = 0.00206(T - 0.5)^{1.33}S/(0.912 + S).$$

The instantaneous growth rate of stage i is given by:

$$g_i = (\ln W_{i+1} - \ln W_i)/D_i$$

where, W_i and W_{i+1} are body carbon weight (μgC) of stage i and stage i + 1, respectively, and D_i is instar duration (day) of stage i. D_i was estimated from the equations of Kang and Kang (1998b).

3. Results

3.1 Environmental variables

Temperature of surface and bottom water ranged

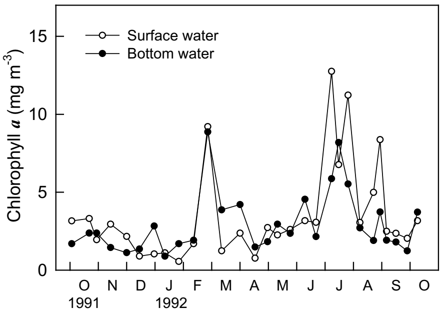

Fig. 3. Seasonal variation in chlorophyll *a* concentration at St. 3.

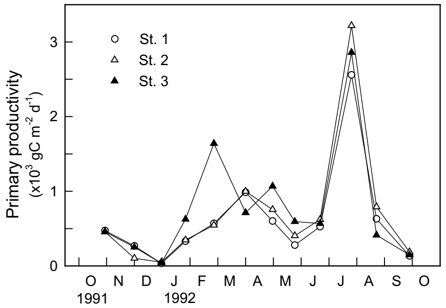

Fig. 4. Seasonal variation of primary productivity at three stations.

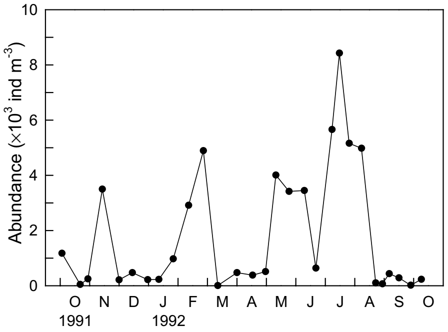

Fig. 5. Seasonal variation in abundance of *Acartia steueri* (nauplii + copepodids + adults).

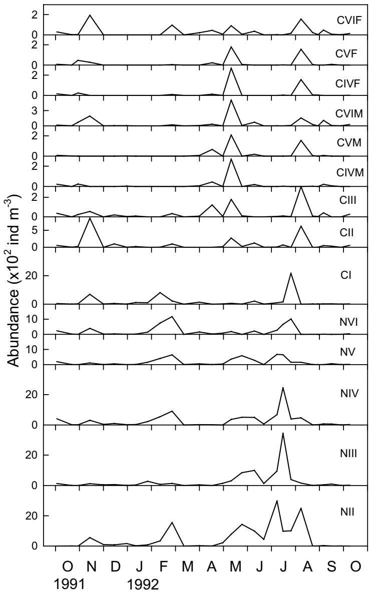

Fig. 6. Seasonal variation in stage-specific abundance of *Acartia steueri* (M: male, F: female).

from 10.2 to 25.4°C (Fig. 2) and salinity changed from 30.4 to 34.7 at St. 3. Chlorophyll *a* concentration of surface and bottom water varied from 1.0 to 9.3 mg chl.*a* m^{-3} at St. 3 (Fig. 3), with higher values in the summer than in the mid-spring, fall and winter (except for other peak in late February). Primary productivity of phytoplankton at the three stations ranged from 33 to 3218 mgC m^{-2}day^{-1}, showing a similar seasonal variation with the chlorophyll *a* concentration (Fig. 4). Mean primary productivity was estimated at 549 mgC m^{-2}day^{-1}, and annual primary productivity at 200 gC m^{-2}yr^{-1}. The daily primary productivity of phytoplankton (PP, mgC m^{-2} day^{-1}) increased linearly with increasing chlorophyll *a* concentration (Chl *a*, mg chl.*a* m^{-2}), and is described as:

$$PP = -9.50 + 25.80\text{Chl } a \quad (r^2 = 0.782; P < 0.01).$$

3.2 Seasonal variations in abundance and body size

Acartia steueri (nauplii + copepodids + adults) were present in the plankton throughout the year. Abundance ranged from 3 to 2204 ind. m^{-3} (mean 437 ind. m^{-3}), with the highest peak in 15 July (8426 ind. m^{-3}), and other peaks in mid-November, late February and May (Fig. 5). Variations in abundance of various developmental stages are shown in Fig. 6. The stage-specific abundance fluctuated greatly with four distinct peaks in November, late February, May and July–August. Without the presence of sequential well-defined pulses of the stage with time we were prevented from performing generation analyses (Liang and Uye, 1996a).

Mean body size of adult *A. steueri* fluctuated seasonally, being inversely related to the water temperature in the field. The body size was larger in the winter and early spring, and was smaller in the summer and fall (Fig. 7).

3.3 Growth rate

Instantaneous growth rate of each developmental stage was calculated on each sampling date and the mean

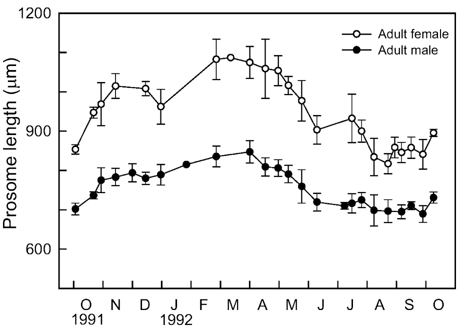

Fig. 7. Seasonal variation in body size of adult copepod *Acartia steueri*.

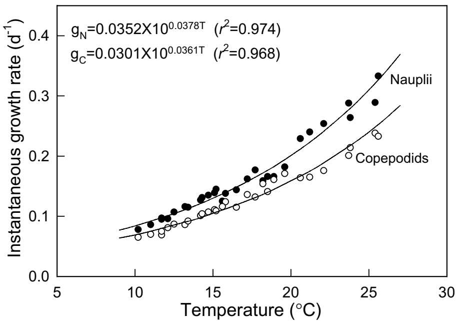

Fig. 8. Relationship between mean instantaneous growth rates of nauplii (g_N) and copepodids (g_C) of *Acartia steueri*.

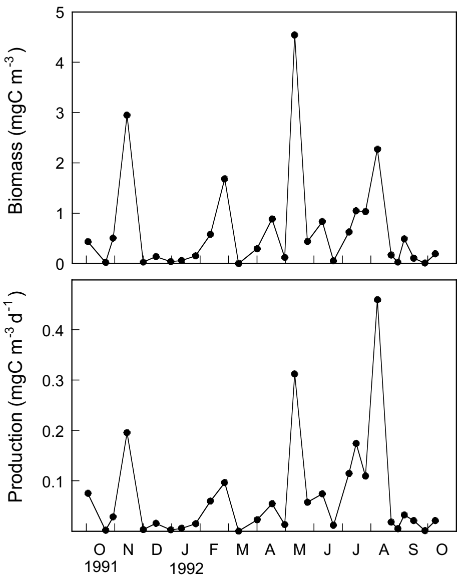

Fig. 9. Seasonal variations in biomass and production rate of *Acartia steueri*.

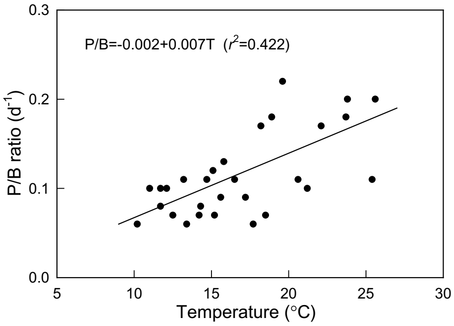

Fig. 10. *Acartia steueri*. Relationship between daily production/biomass ratio (P/B ratio) and water temperature.

growth rates for nauplii and copepodids were plotted against the water temperature (Fig. 8). The growth rates were as follows:

$$g_N = 0.0352 \times 10^{0.0378T} \quad (r^2 = 0.974;\ P < 0.01),$$

$$g_C = 0.0301 \times 10^{0.0361T} \quad (r^2 = 0.968;\ P < 0.01),$$

where, g_N is mean instantaneous growth rate (day^{-1}) of nauplii (from N2 to N6), g_C is mean instantaneous growth rate (day^{-1}) of copepodids, and T is water temperature (°C).

3.4 Seasonal variations in biomass and production rate

Biomass of *A. steueri* ranged from 0.01 to 4.55 mgC m^{-3} (mean 0.68 mgC m^{-3}). The maximum biomass was observed in May, followed by November, early August, May and late February (Table 1; Fig. 9). The pattern of seasonal variation in production rate of *A. steueri* was similar to that of the biomass (Table 1; Fig. 9), but the highest peak was observed in early August (0.46 mgC m^{-3}day^{-1}). Mean daily production rate of *A. steueri* was 68.8 (μgC m^{-3}day^{-1}), and annual production rate was estimated to be 25.1 mgC m^{-3}yr^{-1} (or 166 mgC m^{-2}yr^{-1}) at St. 3. The contribution of nauplii to the population production rate of *A. steueri* was 37.0%, copepodids 49.6% and eggs of adult female 13.4% (Table 1), indicating a relatively minor importance of the egg production of adult female.

A relationship between the ratio of daily production rate to biomass (P/B) and the water temperature (T, °C) was linear (Fig. 10) and was expressed by:

$$P/B = -0.002 + 0.007T \quad (r^2 = 0.422;\ P < 0.01).$$

4. Discussion

The primary productivity of phytoplankton in Ilkwang Bay was higher in the summer, showing the similar trend to the variations of primary production in coastal

Table 1. *Acartia steueri*. Summary of nauplii production (NP, μgC m^{-3}day^{-1}), copepodites production (CP, μgC m^{-3}day^{-1}), egg production (EP, μgC m^{-3}day^{-1}), total secondary production (TSP, μgC m^{-3}day^{-1}) and biomass (B, mgC m^{-3}) at each sampling date at St. 3 in Ilkwang Bay.

Date	NP	CP	EP	TSP	B
October 2, 1991	36.4	28.7	10.3	75.4	0.43
October 21	0.9	0.5	0.6	2.0	0.02
October 29	0.3	27.2	0.9	28.4	0.51
November 13	26.4	105.8	63.3	195.5	2.95
November 30	3.0	0.3	—	3.3	0.03
December 14	4.4	11.3	—	15.7	0.14
December 30	1.9	1.0	—	2.9	0.04
January 11, 1992	1.2	4.9	—	6.1	0.06
January 26	11.7	3.2	—	14.9	0.15
February 10	30.0	29.8	—	59.8	0.58
February 24	48.5	17.6	30.6	96.7	1.68
March 11	0.1	0	—	0.1	0.01
March 31	6.7	1.0	6.1	13.8	0.30
April 16	0.8	43.1	10.8	54.7	0.88
April 29	7.9	2.7	2.4	13.0	0.12
May 10	33.8	247.1	31.3	312.2	4.55
May 24	52.1	3.3	2.2	57.6	0.44
June 9	44.2	19.3	10.7	74.2	0.84
June 21	11.5	0.2	—	11.7	0.05
July 7	105.8	8.3	0.6	114.7	0.63
July 15	160.4	13.6	—	174.0	1.05
July 25	48.6	55.4	5.6	109.6	1.03
August 7	85.8	312.9	60.9	459.6	2.28
August 22	0.8	8.4	9.3	18.5	0.17
August 29	1.5	2.2	1.3	5.0	0.03
September 5	3.1	17.4	11.7	32.2	0.49
September 15	8.5	10.1	2.5	21.1	0.11
September 27	0.4	0.3	0.3	1.0	0.10
October 8	3.7	12.2	5.3	21.2	0.19

—: No adult females in the field.

and semi-enclosed waters in temperate regions (Uye *et al.*, 1983; Lee *et al.*, 1991; Yoo and Shin, 1995). The peak in the late winter at station 3 (Fig. 4) may be due to the higher concentration of chlorophyll *a* concentration (Fig. 3) consisting of the dominant diatoms, *Eucampia zodiacus* and *Chaetoceros didymus* (Kang, 1997), in the inner part of Ilkwang Bay. Seasonal variation of primary productivity was similar to the variation of chlorophyll *a* concentration (Figs. 3 and 4), and the chlorophyll *a* concentration explained 78% of variation in primary productivity in Ilkwang Bay (based on the coefficient of determination in the linear regression between chlorophyll *a* concentration and primary productivity).

In the present study, nauplii, copepodids and adults of *A. steueri* occurred in the plankton in all the seasons. Biomass of *A. steueri* to total biomass of *Acartia*, including *A. omorii*, *A. hudsonica*, *A. pacifica*, *A. erythraea*, *A. negligens* and *A. danae*, collected by a conical type net (45 cm mouth diameter and 330 μm mesh) at the same station in the Ilkwang Bay ranged from 2.1 to 96.7% (Kang, 1997), indicating *A. steueri* might be an important copepods in terms of biomass of genus *Acartia*. In addition, *A. omorii*, one of the dominant calanoid copepods in Korean waters (Kang and Kim, 2002), also occurred in plankton in the winter and early spring with the percent biomass of 3.6 to 100% to the total biomass of *Acartia* in Ilkwang Bay (Kang, 1997). Therefore, the population dynamics and production of *A. omorii* also should be considered in Korean water.

The instantaneous growth rate of nauplii of *A. steueri* at 20°C is higher than that of copepodids (Fig. 8), indicating higher growth rate in nauplii than copepodids. The instantaneous growth rate of nauplii of *A. steueri* is similar to that of *Paracalanus* sp., but low compared to *Centropages abdominalis*, *A. omorii*, and *Calanus sinicus* (Table 2). Also, the rate of growth in copepodids of *A.*

Table 2. Comparison of the instantaneous growth rate (g, day^{-1}) of nauplii and copepodids at 20°C among calanoid copepods with temperature and chlorophyll *a* concentration (Chl *a*, mg chl.*a* m^{-3}).

Species	Temperature range (°C)	Chl *a* range	g		Calculated from
			Nauplii	Copepodids	
Centropages abdominalis	8.9–21.1	0.7–322	0.34	0.45	Liang *et al.* (1996)
Acartia omorii	8.9–24.3	0.7–322	0.42	0.37	Liang and Uye (1996a)
Paracalanus sp.	8.9–28.2	0.7–322	0.21	0.34	Liang and Uye (1996b)
Calanus sinicus	10.3–20.2	?	0.59	1.31 (CI and CII) 0.58 (CIII and CIV) 0.20 (CV)	Uye (1988)
Acartia steueri	10.2–25.4	1.0–9.3	0.20	0.16	This study

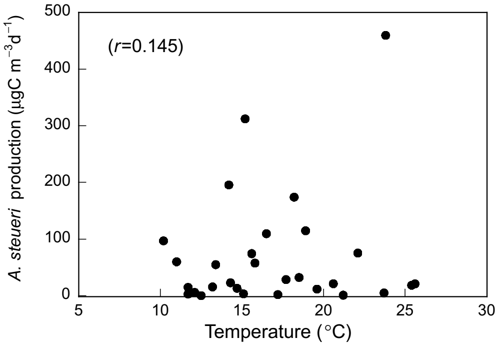

Fig. 11. Production rate of *Acartia steueri* as a function of water temperature.

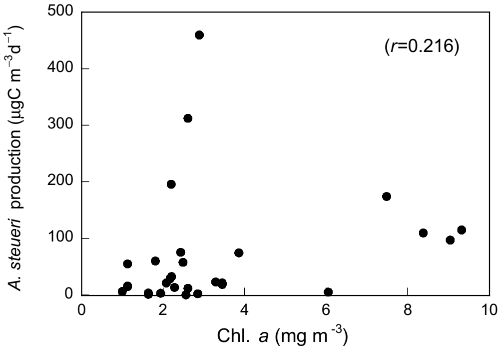

Fig. 12. Production rate of *Acartia steueri* as a function of chlorophyll *a* concentration.

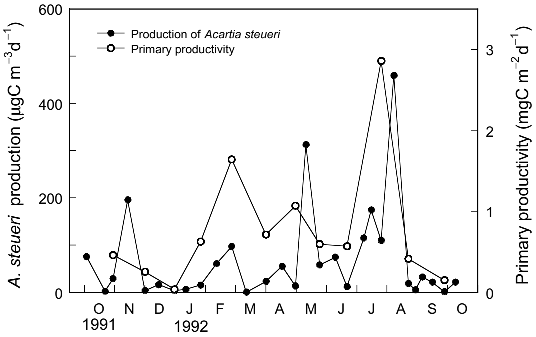

Fig. 13. Seasonal changes in primary productivity and daily production rate of *Acartia steueri* in Ilkwang Bay.

steueri is lower than many other calanoid copepods (Table 2). The post-embryonic development pattern of *A. steueri* was rather equiproportional (Kang and Kang, 1997) than isochronal (Uye, 1980), showing longer stage duration in copepodids than nauplii, which might be related to the lower growth rate in copepodids of *A. steueri*.

The P/B ratio of *A. steueri* at 20°C (0.14 day^{-1}) in the present study is lower than *A. omorii* (0.34 day^{-1}; Liang and Uye, 1996a) and *C. abdominalis* (0.31 day^{-1}; Liang *et al.*, 1996), and similar to *Pseudodiaptomus marinus* (0.17 day^{-1}; Uye *et al.*, 1983). In this study, water temperature accounted for ~42% of the variation of the P/B ratio of *A. steueri*. Thirty two percent of the variation of the P/B ratio of *A. omorii* in Ilkwang Bay was explained by water temperature (Kang, unpublished data). However, Liang and Uye (1996a) reported that ~95% of variation of the P/B ratio of *A. omorii* in Inland Sea of Japan (Fukuyama Harbor) was explained by water temperature, given a high chlorophyll concentration, supporting temperature-dependent production of marine copepods (Huntley and Lopez, 1992). Therefore, effect of water temperature on the variation of the P/B ratio varies with copepod species and research site of the coastal area in temperate region.

The relationship between either the daily production rate of *A. steueri* and the water temperature (Fig. 11) or chlorophyll *a* concentration (Fig. 12) was not significantly correlated, although the specific egg production rate and growth rate were estimated from temperature and/or chlorophyll *a* concentration in this study. This result may be

Table 3. Comparison of copepod production (mgC m^{-3}) among calanoid copepods.

Species	Mean daily production	Annual production	Regions	References
Centropages abdominalis	7.89*	—	Fukuyama Harbor	Liang *et al*. (1996)
Acartia omorii	12.69*	—	Inland Sea of Japan	Liang and Uye (1996a)
Pseudodiaptomus marinus	—	20.7	Inland Sea of Japan	Uye *et al*. (1983)
Calanus sinicus	—	358	Inland Sea of Japan	Huang *et al*. (1993)
Paracalanus sp.	—	734	Inland Sea of Japan	Liang and Uye (1996b)
Acartia steueri	0.069	25.1	Ilkwang Bay, Korea	This study

*Daily production is recalculated from the original data.

Table 4. Comparison of food chain efficiency (FCE), estimated from the original data, among calanoid copepods.

Species	Temperature (°C)	FCE (%)	Regions	References
Acartia clausi	—	0.1	Black Sea	Greze and Baldina (1964)
Acartia clausi	*ca.* 15–18	8	Black Sea	Petipa (1967)
Acartia clausi + *A. tonsa*	3–22	5	Narragansett Bay	Durbin and Durbin (1981)
Calanus pacificus	*ca.* 12–15	3	Off La Jolla	Mullin and Brooks (1970)
Total copepods	*ca.* 11–22	21.7	Inland Sea of Japan	Uye *et al*. (1987)
Acartia steueri	10–26	0.08	Ilkwang Bay, Korea	This study

related to the fact that seasonal variations of biomass (or abundance) of developmental stages and adult females of *A. steueri* are poorly related to water temperature and chlorophyll *a* concentration in the field. Nevertheless, the seasonal variations of the primary productivity of phytoplankton and daily production rate of *A. steueri* at St. 3 (Fig. 13) show that there is an increase of *A. steueri* production followed the elevation of primary productivity in the summer, implying that *A. steueri* population consumes the phytoplankton diets for their growth and reproduction in the summer in Ilkwang Bay.

The production rate of *A. steueri* in Ilkwang Bay (68.8 μgC m^{-3}day^{-1}; 25.1 mgC m^{-3}yr^{-1}; Table 3) in the present study is similar to that of *P. marinus* in the central part of the Inland Sea of Japan (Uye *et al.*, 1983), but is much lower than those of *C. abdominalis* in Fukuyama Harbor (Liang *et al.*, 1996), *A. omorii* (Liang and Uye, 1996a), *C. sinicus* in Kii Channel (Huang *et al.*, 1993), and *Paracalanus* sp. (Liang and Uye, 1996b) in a eutrophic inlet of the Inland Sea of Japan. Considering the primary productivity of phytoplankton (200 gC m^{-2}yr^{-1}) in Ilkwang Bay and depth integrated annual secondary production (166 mgC m^{-2}yr^{-1}) of *A. steueri* at St. 3 (6.6 m of water depth), food chain efficiency (the ratio of primary production to secondary production; Peterson *et al.*, 2002) of *A. steueri* population was 0.08%, showing very low transfer efficiency compared to those of other calanoid copepods (Table 4). These results indicate that the production rate of *A. steueri* in Ilkwang Bay seems to be rather low compared to the potential production of total copepods. So, the other copepods (e.g. *A. omorii*, *Paracalanus* sp. and *C. sinicus*, etc.; Kim *et al.*, 1993; Liang and Uye, 1996a, b; Kang and Kim, 2002) may also be more important in terms of biomass and production in Korean waters. However, our data can be applicable in estimating the production rate of copepods and in better understanding the potential role of *A. steueri* in Korean waters.

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