Scientific note

Chlorophyll specific growth rate and grazing mortality rate of phytoplankton in the shelf water of the Bering Sea in summer

Tsuneo Odate* and Sei-ichi Saitoh

Faculty of Fisheries Hokkaido University, 3-1-1, Minato-cho, Hakodate 041-8611

Abstract: Chlorophyll specific growth rate and grazing mortality rate due to microzooplankton were estimated based on the dilution methods, using surface waters collected at four stations in the continental shelf area of the Bering Sea in summer. Growth rates and grazing mortality rates of phytoplankton communities were ranged between $0.06\,d^{-1}$ and $0.56\,d^{-1}$ and between $0.04\,d^{-1}$ to $0.33\,d^{-1}$, respectively. The high growth rate seems to have resulted from continuous supply of nutrients caused by gentle stratification, which is a favorable condition of the water column for phytoplankton growth. Growth and grazing mortality rates were almost the same at one station, where the most typical summer concentration of chlorophyll a was observed (less than $1\,\mu g\,l^{-1}$), suggesting that the major grazer seems to be microzooplankton in the Bering Sea shelf in summer. On the other hand, the lowest growth rate was obtained in near St. Laurence Island, where higher chlorophyll concentrations more than several $\mu g\,l^{-1}$ occurred. In this water passive sinking of cells seems to become one of controlling factor of phytoplankton abundance.

key wards: Bering Sea shelf, phytoplankton growth, grazing mortality, dilution methods

Phytoplankton biomass in space and time is determined by the difference between algal growth and loss processes, which are mainly due to grazing by zooplankton and to passive sinking. Elevated phytoplankton abundance implies that the algal growth rate has been larger than loss rates in a certain previous period, and does not always imply active growth of the phytoplankton community in a certain period. In contrast, active energy flow from phytoplankton to grazers occurs even though phytoplankton abundance is low when growth rate and grazing mortality rate are high. Consequently, determination of the rates should be necessary to evaluate plankton dynamics.

On the Bering Sea shelf the surface chlorophyll a concentration is usually lower than a few $\mu g\,l^{-1}$ in summer (Sambrotto *et al.*, 1986; Odate 1996; Odate *et al.*, 1999). Several works, however, have shown that high chlorophyll a concentrations locally occur even in this season (*e.g.* Saitoh *et al.*, 1998). The purpose of this study is to compare the growth rate and grazing mortality rate of phytoplankton communities under usual and extremely high chlorophyll levels.

Oceanographic observations were conducted at four stations, OS090, OS107, OS 123, and OS124, in the shelf area of the Bering Sea, from July 19 to 25, 1995, using the

---

* Present address: National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515.
E-mail address: odate@nipr.ac.jp
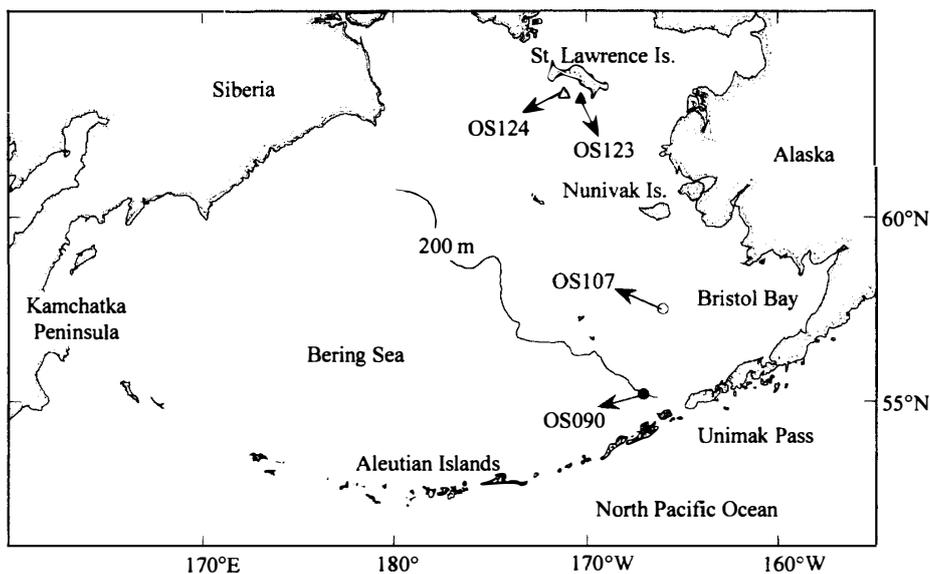
Fig. 1.   Location of sampling stations on the Bering Sea shelf.   Stations OS090 and OS107 were located on the southeast shelf, while Stations OS123 and OS124 were south of St. Lawrence Island.

T/S Oshoro Maru, Faculty of Fisheries, Hokkaido University (Fig. 1).   Seawater temperature and salinity were measured with a CTD-Rosette system (Neil Brown Mark III B).   Seawater samples were collected by Niskin bottles, fitted on the CTD-Rosette system.   Concentrations of nitrate, phosphate, and silicate were measured (Strickland and Parsons, 1972), using aliquotes of the seawater sample.

Surface seawater was collected with a plastic bucket for the dilution experiments to determine growth and grazing mortality rates of natural phytoplankton population (Landry and Hassett, 1982).   The seawater sample was filtered through a 200 μm mesh sized screen (original seawater) to remove macrozooplankton.   Hence, grazing mortality rates detected here were due to microzooplankton.   The original seawater was diluted by the particulate free seawater, which was prepared by filtering with a Whatman GF/F filter using seawater from the same source.   Seawater, which diluted at several different percentages of the original seawater, were incubated in a tank on deck, cooled by the running surface seawater, for one day or two days.   Subsamples (200 ml) were taken every four to six hours from each bottle, and were filtered with Whatman GF/F filters to determine concentrations of chlorophyll a.   The pigments were extracted in N,N-dimethylformamide (Suzuki and Ishimaru, 1990) under darkness at $-20°$C.   Chlorophyll a concentration was determined using a Turner Design Model 10R Fluorometer (Parsons et al., 1984), which was calibrated with pure chlorophyll a (Sigma Chemical Co.).

The vertical difference of temperature between the surface and the depth of 20 m was about 0.5°C at OS090, while water temperature rapidly decreased from 9.1°C to 1.3°C between 15 and 21 m at OS107, from 2.7°C to -1.1°C between 15 and 20 m at OS123, and from 2.1°C to -1.4°C between 10 and 21 m at OS124 (Fig. 2a).   Sharp increases of salinity with depth coincided with the rapid decreases of temperature at OS 107, OS123, and OS124 (Fig. 2b).   Salinity gradually increased with depth below 20 m
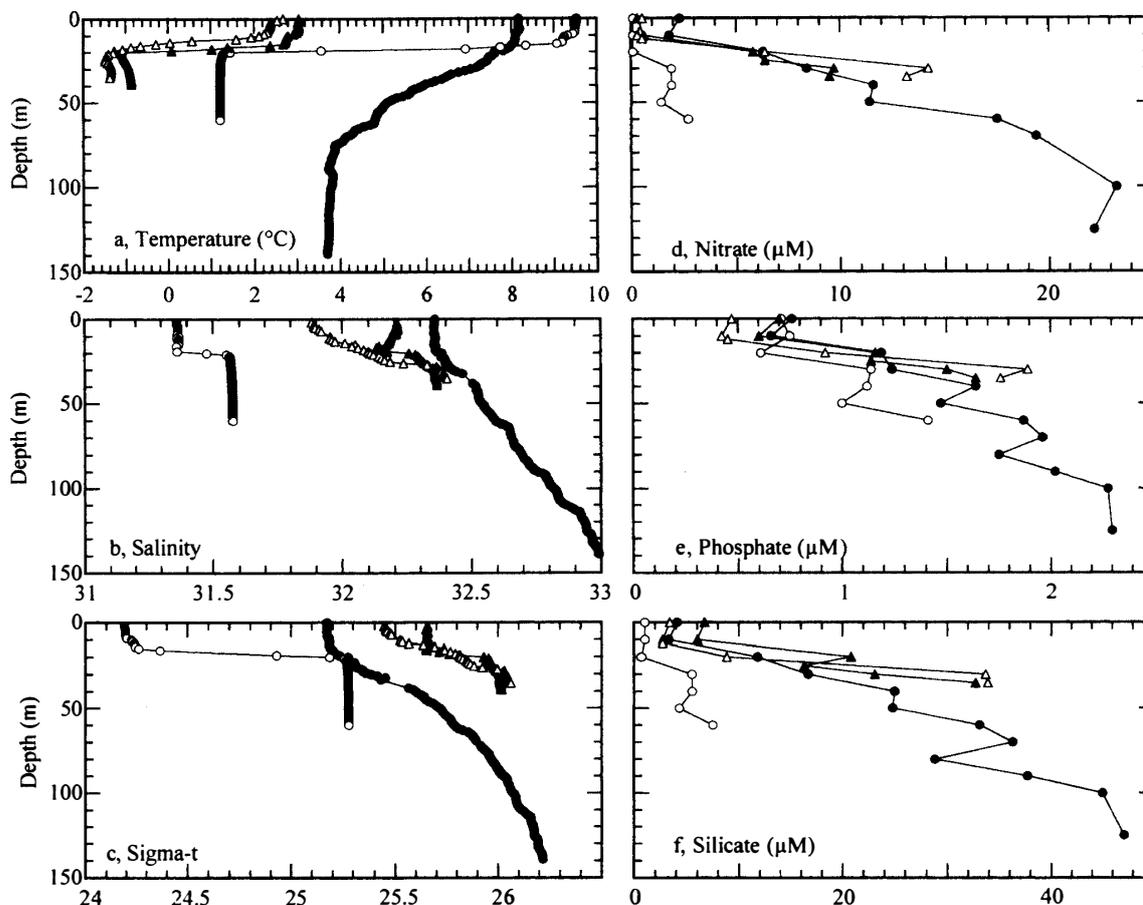
Fig. 2. Vertical profiles of temperature (a), salinity (b), sigma-t (c), nitrate (d), phosphate (e), and silicate (f). Stations OS090, OS107, OS123, and OS124 are represented by closed circles, open circles, closed triangles, and open triangles, respectively.

at OS090. As a result, strong pycnoclines occurred in the depths between 10 and 20 m at OS107, OS123, and OS124 (Fig. 2c).

In the top 10 m, concentrations of nitrate were about $2\,\mu$M at OS090, but less than $1.0\,\mu$M at the other stations (Fig. 2d). In particular, nitrate was depleted at the surface of OS107. Concentrations of phosphate were between 0.6 and $0.8\,\mu$M in the top 10 m of OS090, OS107, and OS123 (Fig. 2e). Concentrations were between 0.4 and $0.5\,\mu$M in the similar layer of OS124. Concentration of silicate was less than $0.5\,\mu$M in the top 10 m at OS107 (Fig. 2f). At the other stations, the concentrations were more than 1 μM in the same layer.

During the incubation experiments, chlorophyll a concentration increased in all bottles. One example, which was obtained at OS090, is shown in Fig. 3. Growth rate (y intercept) and grazing mortality rate (slope) were estimated plotting the apparent growth rates for each dilution factor against the fraction of original seawater (Fig. 4). Growth rate of $0.36\,d^{-1}$ and mortality rate of $0.33\,d^{-1}$ were estimated at OS107, where initial chlorophyll a concentration was $0.61\,\mu g\,l^{-1}$ and the lowest among the four surveyed stations (Table 1). The highest growth rate of $0.56\,d^{-1}$ was estimated at OS 090, where initial concentration of chlorophyll a was $1.1\,\mu g\,l^{-1}$. At this station the
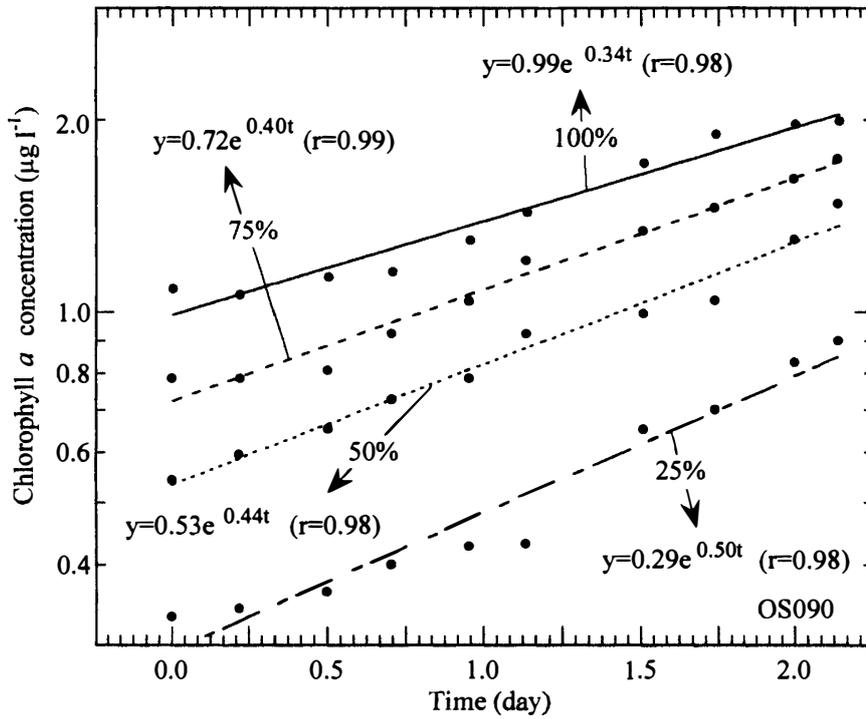
Fig. 3. Example of temporal changes of chlorophyll a concentration during the incubation experiments using the surface water at Station OS090. Equations represent exponential curve fits between time (t) and chlorophyll a concentration (y).
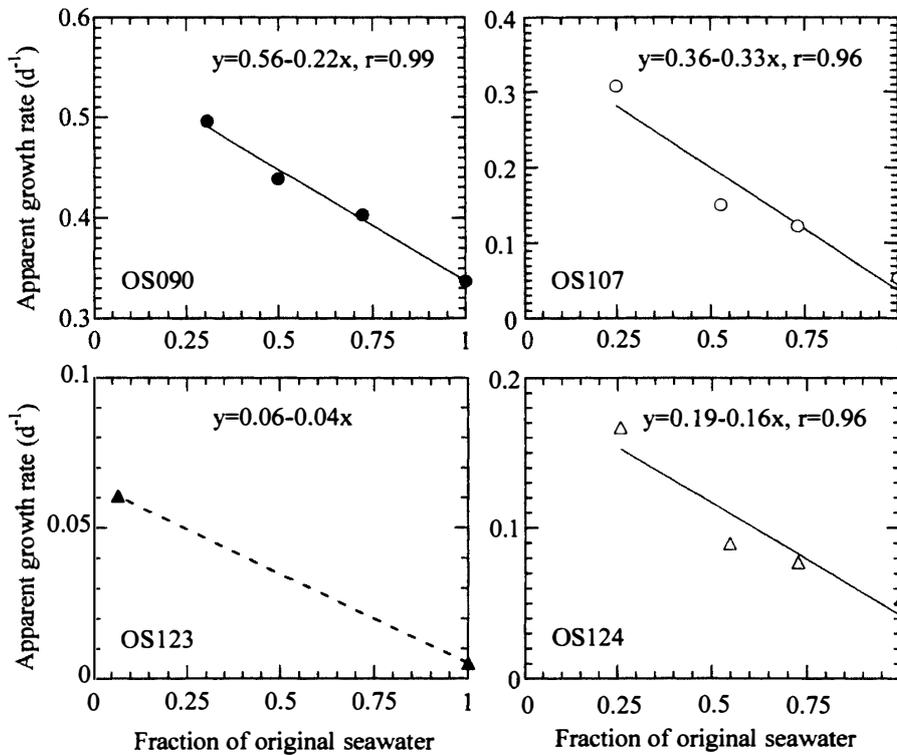
Fig. 4. Relationship between fraction of original seawater and apparent growth rate at Station OS090, OS 107, OS123, and OS124. Solid lines represent the equation of the linear fit. Broken line simply connects two points.

Table 1. Summary of dilution experiments in the Bering Sea. P_0, initial chlorophyll a concentration. k, algal growth rate $\pm 95\%$ confidence interval (CI). g, grazing mortality rate $\pm 95\%$ CI. r, correlation coefficient.

Station	Initial chlorophyll a (P_0) $(\mu g\,l^{-1})$	Algal growth rate (k) $(d^{-1} \pm 95\% \,CI)$	Grazing mortality rate (g) $(d^{-1} \pm 95\% \,CI)$	r
OS090	1.1	0.56 ± 0.05	0.22 ± 0.07	0.99
OS107	0.61	0.36 ± 0.17	0.33 ± 0.25	0.96
OS123	21	0.06*	0.04*	
OS124	4.4	0.19 ± 0.10	0.16 ± 0.14	0.96

* caluculated based on two points.

grazing mortality rate was $0.22\,d^{-1}$. The highest initial concentration of chlorophyll a of $21\,\mu g\,l^{-1}$ was observed at OS123 south of St. Lawrence Island, where original seawater (100%) and seawater diluted at ca. 5% of the original seawater were incubated for two days (Gallegos, 1989). Based on the line connecting the two points, growth rate and mortality rate were estimated as $0.06\,d^{-1}$ and $0.04\,d^{-1}$, respectively, which were the lowest among the surveyed stations. The initial chlorophyll a concentration was $4.4\,\mu g\,l^{-1}$ at OS124, where growth rate and grazing mortality rate were estimated to be $0.19\,d^{-1}$ and $0.16\,d^{-1}$, respectively.

The present study covered a wide range of chlorophyll a concentrations, from <1.0 $\mu g\,l^{-1}$ to $>20\,\mu g\,l^{-1}$, although experiments were conducted at only four stations. It is known that surface chlorophyll a concentration is usually less than $2\,\mu g\,l^{-1}$ on the Bering Sea shelf in summer (Sambrotto et al., 1986; Odate, 1996; Odate et al., 1999). Similar concentrations were observed at OS090 and OS107. Chlorophyll concentrations observed south of St. Laurence Island were 4.4 and $21\,\mu g\,l^{-1}$, which were considered to be high in summer. The elevated phytoplankton abundance resulted from the coastal upwelling (Saitoh et al., 1998).

Growth rates and grazing mortality rates of the phytoplankton community estimated in the present study were between 0.06 and $0.56\,d^{-1}$ and between 0.04 and $0.33\,d^{-1}$, respectively. These values are comparable to previous works conducted in high latitude waters, following similar methods. For instance, Paranjape (1989) showed these rates between 0.06 and $0.34\,d^{-1}$ and 0.08 and $0.17\,d^{-1}$, respectively, in the eastern Canadian Arctic. Tsuda and Kawaguchi (1997) found growth rates mainly between 0.1 and $0.4\,d^{-1}$ and grazing mortality rates mainly between 0.0 and $0.3\,d^{-1}$ in the Southern Ocean in the austral summer.

Growth rate was considerably higher than grazing mortality rate at OS090. Vertical stratification of the water column was weaker (Fig. 2c) and a slightly higher surface concentration of nitrate remained (Fig. 2d) at OS090 than at the other stations. The high growth rate seems to have resulted from continuous supply of nutrients caused by gentle stratification, which is a favorable condition of the water column for phytoplankton growth. If these rates continued for one week, chlorophyll a concentration increased by one order of magnitude.

Almost the same rates were observed between growth and grazing mortality rates

at the other stations. This means that phytoplankton grows at a certain rate, but abundance does not increase since microzooplankton grazes upon phytoplankton at a similar rate. Chlorophyll a concentration was less than $1\,\mu g\,l^{-1}$ in the surface water at OS107, where the water column was highly stratified with nutrient depleted surface water. The water column properties represented the summer water column of the Bering Sea shelf (Sambrotto et al., 1986; Whitledge et al., 1986; Odate, 1996; Odate et al., 1999), and continued throughout the summer (Sambrotto et al., 1986; Whitledge et al., 1986). The low and constant phytoplankton abundance in summer seems to be mainly controlled by microzooplankton grazing as observed by Tsuda and Kawaguchi (1997) in the Southern Ocean.

On the other hand, fairly low growth and grazing mortality rates were observed at OS123 and OS124, where the initial concentrations of chlorophyll a were higher than the usually observed values on the Bering Sea shelf in summer (Sambrotto et al., 1986; Odate 1996; Odate et al., 1999). These high chlorophyll concentrations indicated local phytoplankton bloom caused by coastal upwelling, which occurred south of St. Laurence Island (Saitoh et al., 1998). The low growth rates and low concentrations of nutrients (Fig. 2d, e, f) indicated that the phytoplankton bloom had ended in this water. Usually phytoplankton abundance rapidly decreases after blooms. Consequently, passive sinking of cells should become the major controlling factor if the phytoplankton abundance decreases to the typical level at these stations since large size fraction predominates when total chlorophyll concentration is higher than several $\mu g\,l^{-1}$ (Odate, 1996).

The present results showed that phytoplankton cells in the large abundance did not have high growth rate. A fairly high growth rate was obtained from phytoplankton at the chlorophyll concentration of about $1\,\mu g\,l^{-1}$. These observations suggest that growth rate is high in the initial phase and becomes low in the late phase of blooms although they were obtained at four stations. Further investigations of phytoplankton growth rate and grazing mortality rate should be integrated to recognize the development of phytoplankton blooms in the polar sea area.

Acknowledgments

References

Gallegos, C.L. (1989): Microzooplankton grazing on phytoplankton in the Rhode River, Maryland: nonlinear feeding kinetics. Mar. Ecol. Prog. Ser., 57, 23–33.
Landry, M.R. and Hassett, R.P. (1982): Estimating the grazing impact of marine micro-zooplankton. Mar.

Biol., **67**, 283–288.

Odate, T. (1996): Abundance and size composition of the summer phytoplankton communities in the western North Pacific Ocean, the Bering Sea, and the Gulf of Alaska. J. Oceanogr., **52**, 335–351.

Odate, T., Shiga, N., Saitoh, S., Miyoi, T. and Takagi, S. (1999): Distribution of phytoplankton abundance and physical properties in the southeastern shelf of the Bering Sea in summer. Polar Biosci., **12**, 1–14.

Paranjape, M. (1989): Grazing by microzooplankton in the eastern Canadian arctic in summer 1983. Mar. Ecol. Prog. Ser., **40**, 239–246.

Parsons, T.R., Maita, Y. and Lalli, C.M. (1984): A Manual of Chemical and Biological Methods for Seawater Analysis. Oxford, Pergamon Press, 173 p.

Saitoh, S., Eslinger, D.L., Sasaki, H., Shiga, N., Odate, T. and Miyoi, T. (1998): Satellite and ship observation of coastal upwelling in the St. Lawrence Island Polynya (SLIP) area in summer, 1994 and 1995. Mem. Fac. Fish. Hokkaido Univ., **45**, 18–23.

Sambrotto, R.N., Niebauer, H.J., Goering, J.J. and Iverson, R.L. (1986): The relationship among vertical mixing, nitrate uptake, and growth during the spring bloom on the southeast Bering Sea middle shelf. Cont. Shelf Res., **5**, 161–198.

Strickland, J.D.H. and Parsons, T.R. (1972): A practical handbook of seawater analysis. 2nd ed. Fish. Res. Bd. Canada Bull., **167**, 1–311.

Suzuki, R. and Ishimaru, T. (1990): An improved method for the determination of phytoplankton chlorophyll using N,N-dimethylformamide. J. Oceanogr. Soc. Jpn., **46**, 190–194.

Tsuda, A. and Kawaguchi, S. (1997): Microzooplankton grazing in the surface water of the Southern Ocean during an austral summer. Polar Biol., **18**, 240–245.

Whitledge, T.E, Reeburgh, W.S. and Walsh, J.J. (1986): Seasonal inorganic nitrogen distributions and dynamics in the southeastern Bering Sea. Cont. Shelf Res., **5**, 109–132.