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Occurrence, Seasonal Changes and Vertical Distribution of Silica-scaled Chrysophytes in a Small Fish-free Pond in Japan

Han Soon Kim* **and Noriko Takamura**[1]

Department of Biology, College of Natural Sciences, Kyungpook National University, Taegu 702-701, Korea;
[1]National Institute for Environmental Studies, Tsukuba 305, Japan

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Vertical distribution
Fish-free pond

Occurence, seasonal changes and vertical distribution of the silica-scaled chrysophytes in a small fish-free pond were studied using electron microscopy (EM) and light microscopy (LM) from October 1998 to July 1999. The phytoplankton community was characterized by Chrysophyta and Cryptophyta. Ten species of the silica-scaled chrysophytes of genera *Mallomonas*, *Synura*, *Chrysosphaerella* and *Spiniferomonas* were identified by EM, and the most abundant species were *Mallomonas akrokomos* and *M. portae-ferreae*. The maximum population density of *M. akrokomos* was observed in December and several peaks appeared periodically at about one to two month intervals, whereas *M. portae-ferreae* developed the maximum density in March. The diurnal vertical distribution of *M. akrokomos* exhibited clear downward migration at night and slightly upward migration in the morning. A complex interaction among physico-chemical and biological factors seemed to affect the vertical distribution of *M. akrokomos*. However, the seasonal changes of *M. akrokomos* did not show significant correlations with the physico-chemical and some biological factors. Although *M. akrokomos* was evenly distributed throughout the water column during some experimental periods, the diurnal patterns found in the two diurnal cycles showed consistency in that it clearly avoided the surface water during the day. This suggested that *M. akrokomos* may be a shade plankton with maximum densities below surface layer.

Silica-scaled chrysophytes including Synurophyceae often show large biomass and high species diversity in some freshwater lakes and reservoirs (Takahashi, 1978; Arvola, 1986; Kristiansen, 1986; Eloranta, 1989). However, the ecological importance of this often ignored group is underappreciated because limnological studies often employ the light microscope only, and correct identification of these organisms is questionable (Sandgren, 1988).

The silica-scaled chrysophytes had long been considered as a phytoplankton group primarily restricted to cold, oligotrophic conditions and mainly occurring in the winter and early spring (Kristiansen, 1975; Kristiansen & Takahashi, 1982). However, more recently, a rich silica-scaled chrysophyte flora has been described from tropical regions as well as during the summer in temperate regions, and in eutrophic waterbodies (Kristiansen, 1988; Cronberg, 1989; Saha & Wujk, 1990). Additionally, some species of silica-scaled chrysophytes can form dense concentrations during the summer (Classen & Bernhardt, 1982; Pick & Nalewajko, 1984; Hoffmann & Wille, 1992).

Although many studies have been carried out on the effects of variable environmental factors controlling the seasonal changes, vertical distribution and migration of the flagellate phytoplankton (Reynolds, 1984; Jones, 1988; Sandgren, 1988; Hoffmann & Wille, 1992; Siver, 1995; Péterfi & Momeu, 1996), this group is the most poorly known among freshwater phytoplankton groups with regards to their nutrition and ecology (Sandgren, 1988). Particularly, the quantitative dynamics of this group still largely remains to be unknown. This is mainly because their ecological study by LM is hampered by their small size which makes their preservation and identification difficult, and the examination by EM is necessary for reliable identification, and also electron microscopes are seldom available in limnological studies.

The purpose of this study was to investigate the occurrence, vertical distribution and seasonal changes of the silica-scaled chrysophytes in a small, shallow, fish-free pond in relation to some physico-chemical and biological factors.

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* To whom correspondence should be addressed.
Tel: 82-53-950-5344, Fax: 82-53-953-3066
E-mail: kimhsu@knu.ac.kr

Study Area

The present investigation was carried out in a small artificial experimental pond in the National Institute for Environmental Studies (NIES), Tsukuba, Japan (140° 07′ E, 36° 02′ N). The pond was constructed in the wetland and filled with ground water in 1980. It has a maximum volume of 5,500 m^3, maximum depth of 4.2 m, mean depth of 1.4 m and surface area of 3,894 m^3. The littoral zone shallower than 70 cm is primarily covered with emergent aquatic macrophytes. Two artificial channels are located in the east part of the pond, through which pumped-up ground water flows at a rate of 74 m^3 per day (for a more detailed description see Iwakuma et al., 1989). Since the time of the pond construction fish has been absent. Larvae of a phantom midge, *Chaoborus flavicans,* have maintained a high density every year since it has first appeared in July 1981. The zooplankton community is dominated by two cladocerans, *Daphnia rosea* and *Ceriodaphnia reticulata*, a cyclopoid copepod, *Tropocyclos prasinus* and calanoid copepod, *Acanthodiaptomus pacificus* (Iwakuma et al., 1989; Xie et al., 1998a). During the summer period, a dense algal bloom is caused by *Ceratium hirundinella* (Xie et al., 1998b).

Materials and Methods

Seasonal observations were carried out from October 1998 to July 1999. Samples for phytoplankton and nutrient analyses were taken with an acrylic column sampler (7 cm in inner diameter, 2.5 m long) at weekly intervals through the water column between 1400-1600 h. The diurnal observations were undertaken on December 18, 1998 and April 9, 1999 and samples were collected with a polyvinyl chloride tube (3 cm in inner diameter) using a vacuum pump from five depths (surface, 1, 2, 3 and 4 m). Samples for phytoplankton were fixed with Lugol's iodine solution and counted at a magnification of 400× using an inverted microscope after sedimentation using the Utermöhl (1958) method. The abundance of phytoplankton was calculated from the cell countings of 100 randomly selected fields. For transmission electron microscopy, samples were mounted on formvar-coated grids, desiccated in an oven (60℃) and coated with carbon. Samples for scanning electron microscopy were placed on a coverglass, air-dried and gold-coated. Electron micrographs were taken with a Hitachi H-7100 (TEM) and a Hitachi S-570 (SEM) (Inst. of Basic Science, Kyungpook National Univ.). Ciliates in all fields of chamber were counted at magnifications of 100× or 200× using the same phytoplankton samples. Zooplankton samples were collected by the same method as that used for phytoplankton sampling and filtered through a plankton net (mesh size 40 µm). Collected zooplanktons were fixed with sugar-formalin (12%) and counted with a binocular microscope. Water temperature, dissolved oxygen, pH and irradiance were measured with an oxygen electrode (YSI Model 57), pH meter (MP120) and quantum sensor (LI-COR, UWQ-190), respectively. Total nitrogen, total phosphorus and dissolved nutrients analyses were performed according to the standard methods (APHA, 1992). Correlation coefficents were calculated using the SPSS v.7.0 program.

Results

Physical and chemical conditions

Physical and chemical factors measured in the study are shown in Table 1. During the study period, water temperature and pH ranged between 4.8-23.4℃ and 6.5-8.7, respectively. Total nitrogen ranged from 114.9 µg/l (April 1999) to 543.8 µg/l (December 1998) and total phosphorus from 6.8 µg/l (April 1999) to 69.2 µg/l (June 1999). During the diurnal investigations, all of the factors except irradiance were nearly uniform at all water depths (Table 1).

Occurrence of species

In this study, 10 taxa of silica-scaled chrysophytes were found including seven species of *Mallomonas*, one of *Synura*, one of *Chrysosphaerella* and one of *Spiniferomonas*. Electron micrographs of the cells and scales of each species of silica-scaled chrysophytes are shown in Figs. 1-3.

Four taxa of *Mallomonas*, including *M. caudata* Ivanov (Fig. 1A), *M. paxillata* (Bradley) Péterfi & Momeu (Fig. 1B), *M. tonsurata* Teiling emend. Krieger (Fig. 1C), and *M. papillosa* var. *papillosa* Harris & Bradley (Fig. 1E), were found only a few scales and bristles. A few cells of *M. heterospina* Lund (Fig. 1D) per liter of water were observed during the winter. In our study pond, the small and large-sized cells of *M. akrokomos* Ruttner (Figs. 1F, 2A) were observed and appeared to be the most abundant species among the silica-scaled chrysophytes. Most of the features of the scales and bristles of *M. portae-ferreae* Péterfi & Asmund (Figs. 2B-D, 3A-D) observed in this study resembled the previous descriptions. However, the results from SEM observations showed that our material has some unique features; these include ornamentation with a row of minute teeth along the submarginal ribs (Figs. 2D, 3A), a perpendicular arrangement of rear scales to the longitudinal axis of the cell (Figs. 2B, D), circular pits along with a concave margin of a dome in the anterior scales (Fig. 3A) and five minute teeth at the tip of the subapical teeth (Fig. 3D). *Synura petersenii* f. *petersenii* Korshikov (Fig. 3E), *Spiniferomonas trioralis* Takahashi (Fig. 3F) and *Chrysosphaerella brevispina* Korshikov emend. Harris et Bradley (Fig. 3G) were found only a few cells and scales at our study pond.

Seasonal changes and vertical distribution of dominant species

The maximum and minimum of the total standing crop were observed on February 17 and April 16, 1999,

Table 1. Vertical distributions of water temperature (WT, ℃), pH, conductivity (μS cm^{-1}), light intensity (μE $m^{-2}s^{-1}$), dissolved oxygen (DO, μg l^{-1}), total nitrogen (TN), total phosphorus (TP), nitrate (NO_3-N), ammonium (NH_4-N) and phosphate (PO_4-P) concentrations (μg l^{-1}) during the study

Date	Time	Depth (m)	WT	pH	EC	Light	TN	TP	NO_3-N	NH_4-N	PO_4-P
11 Nov. 1998		0	14.3	6.5	135.9	267.0	473.6	11.7	124.5	99.4	1.0
		1	14.3	6.5	135.8	102.0	589.9	12.7	127.0	98.1	1.3
		2	14.3	6.5	135.6	46.0	558.6	12.2	121.0	89.1	0.6
		3	14.2	6.6	135.7	25.0	485.5	11.6	121.3	89.8	1.1
		4	14.2	6.6	135.0	22.0	451.7	11.3	119.5	84.4	1.1
25 Nov. 1998		0	10.1	6.7	124.3	1287.0	456.8	10.6	127.2	99.0	0.9
		1	9.5	6.7	123.5	524.0	487.7	14.9	124.7	84.4	0.0
		2	9.2	6.7	116.8	410.0	429.5	10.4	125.2	79.1	0.5
		3	9.1	6.7	115.4	189.0	438.5	10.4	124.2	77.4	0.5
		4	9.1	6.8	115.0	112.0	436.9	15.9	125.6	78.4	0.9
18 Dec. 1998		0	7.3	6.9	104.6	304.0	569.0	9.5	134.8	109.1	1.2
		1	6.8	6.7	109.1	62.0	642.6	10.8	136.3	109.4	1.1
		2	6.6	6.8	108.3	26.0	499.2	10.3	135.2	109.2	1.4
		3	6.4	6.8	108.1	12.0	509.5	12.5	136.3	109.4	1.1
		4	6.4	6.7	108.0	9.0	498.8	17.6	136.3	86.9	1.7
29 Dec. 1998		0	7.8	7.2	113.4	984.0	463.2	9.5	149.8	91.2	1.6
		1	5.4	7.0	104.4	430.0	479.0	10.1	145.6	78.8	1.3
		2	5.1	7.0	103.4	210.0	451.1	9.5	146.3	75.7	1.2
		3	5.0	7.1	103.2	111.0	455.5	9.5	146.4	78.0	1.0
		4	5.1	7.0	103.0	79.0	445.2	9.7	145.1	77.0	1.5
13 Jan. 1999		0	6.5	7.9	169.8	855.1	414.6	10.1	144.8	62.2	1.1
		1	4.7	7.4	169.2	367.9	498.4	10.6	144.8	59.7	1.1
		2	4.3	7.4	166.9	162.3	453.6	10.6	147.1	62.6	1.0
		3	4.3	7.1	167.0	72.5	441.5	10.3	143.8	61.1	1.0
		4	4.3	7.1	165.0	53.9	451.8	11.2	142.7	60.9	1.6
27 Jan. 1999		0	7.4	7.6	109.8	202.0	410.4	11.2	137.5	49.5	1.9
		1	5.7	7.4	103.7	67.4	415.2	24.4	134.1	47.6	1.0
		2	5.3	7.4	102.8	37.8	449.7	11.6	132.6	49.2	1.0
		3	5.2	7.3	102.4	18.5	416.8	10.9	135.6	48.2	0.8
		4	5.2	7.2	102.0	5.7	413.1	11.2	134.7	49.5	0.9
10 Feb. 1999		0	7.5	7.0	115.0	977.4	373.0	18.9	116.0	33.9	1.2
		1	5.7	7.1	104.4	422.0	474.0	13.1	116.9	33.5	1.2
		2	5.3	7.1	103.2	184.0	436.0	13.1	116.8	31.3	1.0
		3	5.1	7.2	102.5	84.7	409.3	13.1	114.6	32.5	1.3
		4	5.1	7.0	102.0	54.2	395.7	12.7	115.2	33.0	0.8
25 Feb. 1999		0	7.1	7.1	105.8	1045.0	507.3	13.0	93.6	43.3	1.4
		1	7.1	7.0	107.9	407.1	432.6	12.7	95.7	39.0	0.8
		2	6.7	7.1	106.1	159.9	387.0	12.1	95.0	37.8	0.9
		3	6.0	7.2	103.9	98.4	401.8	11.7	97.3	40.4	0.9
		4	6.0	7.2	103.5	55.1	411.5	12.6	95.8	40.0	0.8
12 Mar. 1999		0	9.4	6.6	123.9	574.1	354.0	11.6	79.0	42.0	1.5
		1	7.9	6.8	111.6	222.0	354.0	10.4	77.0	39.0	1.0
		2	7.2	7.0	108.9	101.0	438.0	14.4	81.0	41.0	1.0
		3	7.1	7.1	108.4	53.0	393.0	11.6	80.0	42.0	1.9
		4	7.1	7.1	108.3	38.0	368.0	10.9	79.0	39.0	1.0
26 Mar. 1999		0	12.5	7.4	116.0	183.0	391.0	29.2	73.0	19.0	1.5
		1	10.8	7.3	112.0	83.0	473.0	11.5	71.0	39.0	1.5
		2	9.6	7.4	110.0	29.0	446.0	11.4	71.0	41.0	1.7
		3	8.9	7.4	109.0	15.0	373.0	10.0	72.0	43.0	1.6
		4	8.8	7.4	108.0	13.0	379.0	10.6	71.0	42.0	1.4
18 Dec. 1998	5:00	0	6.5	6.4	9.48	50.0	546.0	12.8	155.5	98.4	1.1
		1	6.5	6.6	6.86	24.1	537.6	13.6	138.8	92.6	1.5
		2	6.5	6.7	6.58	12.3	537.6	9.9	138.2	90.2	1.5
		3	6.5	6.8	7.67	5.4	601.5	9.3	139.5	91.8	1.9
		4	6.5	6.8	5.50	3.8	506.2	11.8	137.0	89.7	1.4
	8:00	0	6.4	6.6	9.48	731.3	527.7	12.5	138.3	98.1	1.1
		1	6.4	6.6	6.86	278.7	514.1	10.4	137.6	74.2	0.8
		2	6.4	6.8	6.58	125.3	501.3	10.2	137.5	79.0	1.1
		3	6.4	6.8	7.67	56.2	505.4	12.6	138.5	81.6	0.9
		4	6.4	6.8	5.50	37.3	491.7	9.4	137.1	88.3	1.0

Table 1. Continued

Date	Time	Depth (m)	W.T.	pH	DO	Light	TN	TP	NO_3-N	NH_4-N	PO_4-P
	11:00	0	8.5	6.2	7.70	912.4	505.2	8.1	136.2	94.6	2.9
		1	6.7	6.4	7.16	470.4	515.1	10.3	136.0	91.9	1.3
		2	6.5	6.5	6.44	222.3	517.1	11.3	136.1	93.5	1.1
		3	6.4	6.7	6.05	94.8	545.9	12.5	136.2	92.7	1.3
		4	6.4	6.8	6.37	69.0	516.9	10.2	136.3	93.5	1.2
	14:00	0	7.3	6.9	6.85	303.5	569.0	9.5	134.8	109.1	1.2
		1	6.8	6.7	6.14	61.5	642.6	10.8	136.3	109.4	1.1
		2	6.6	6.8	6.42	26.2	499.2	10.3	135.2	109.2	1.4
		3	6.4	6.8	6.40	12.3	509.5	12.5	136.3	109.4	1.1
		4	6.4	6.7	6.09	9.0	498.8	17.6	136.3	86.9	1.7
	17:00	0	6.7	6.9	6.92	43.0	664.8	12.3	136.6	93.6	1.8
		1	6.7	6.7	6.68	21.0	493.6	9.7	136.1	88.8	0.7
		2	6.5	6.8	6.57	8.0	494.5	10.9	136.3	88.5	1.7
		3	6.5	6.8	5.30	2.0	510.5	12.4	136.8	90.2	1.3
		4	6.6	6.7	5.27	0.0	623.4	10.2	136.0	91.0	1.8
	23:00	0	6.3	7.2	10.90		505.8	10.7	136.9	88.3	1.7
		1	6.7	6.9	7.06		532.7	10.9	136.3	63.5	1.9
		2	6.6	6.9	6.29		518.7	9.6	136.0	90.2	1.5
		3	6.5	7.0	6.19		503.8	10.7	135.5	90.5	1.8
		4	6.5	6.9	6.11		508.1	11.6	136.3	91.9	1.2
9 Apr. 1999	5:00	0	11.0	7.1	6.65	98.3	363.3	8.4	55.0	34.5	1.7
		1	11.1	7.2	6.83	25.9	464.5	6.1	43.7	33.0	1.7
		2	11.0	7.3	6.63	14.5	391.2	7.8	41.4	32.4	1.5
		3	10.9	7.4	6.78	7.4	412.1	6.9	41.8	37.4	1.7
		4	10.8	7.7	6.12	7.1	395.8	7.4	37.9	27.9	1.2
	8:00	0	11.0	8.1	6.83	1027.0	458.5	8.5	39.7	34.0	1.8
		1	10.9	8.0	6.96	462.4	317.1	4.7	37.4	25.9	0.9
		2	10.9	8.0	7.21	195.5	296.0	5.2	37.2	26.5	1.1
		3	10.7	7.9	6.67	95.9	300.0	4.4	36.6	25.4	0.9
		4	10.7	7.9	5.68	67.1	317.7	8.4	33.5	25.9	1.8
	11:00	0	11.9	7.9	6.71	1807.0	583.1	6.2	39.6	42.6	2.0
		1	11.3	7.7	6.48	907.9	307.3	4.2	37.1	26.3	1.3
		2	11.0	7.8	6.45	467.6	319.3	4.6	37.1	25.8	1.2
		3	10.8	7.7	7.13	255.2	287.6	4.3	35.9	24.5	1.1
		4	10.7	7.7	6.42	187.5	302.6	4.7	34.2	24.6	1.1
	14:00	0	14.1	7.7	7.34	1507.0	595.2	6.3	43.1	46.0	2.0
		1	11.7	7.6	6.67	716.8	355.0	5.4	38.7	29.1	1.6
		2	11.2	7.6	6.91	260.1	361.2	6.2	38.8	30.4	2.1
		3	11.0	7.6	6.87	93.2	411.3	4.0	37.4	33.2	1.4
		4	10.9	7.6	6.27	66.4	301.3	4.2	34.6	26.0	1.4
	17:00	0	15.0	7.8	6.95	470.0	292.5	10.5	39.5	28.7	1.9
		1	12.3	7.7	7.16	91.6	300.0	4.9	38.1	26.1	1.0
		2	11.4	7.6	6.93	29.8	290.8	4.9	38.4	25.8	1.0
		3	11.0	7.7	6.86	15.3	287.5	4.9	37.3	24.7	2.3
		4	10.9	7.6	7.16	10.9	309.1	8.7	36.6	25.4	1.2
	23:00	0	12.5	7.8	7.20		288.8	11.2	38.3	27.4	1.7
		1	12.3	7.3	6.98		329.5	10.1	39.6	34.0	1.6
		2	11.4	7.4	7.31		286.5	10.2	38.5	30.1	1.7
		3	11.1	7.5	7.52		275.5	9.3	35.9	27.0	1.6
		4	10.9	7.5	7.21		282.0	14.6	35.2	27.5	1.5

respectively (Fig. 4). The phytoplankton community was dominated by Chrysophyta and Cryptophyta (Fig. 5A). *Mallomonas akrokomos* and *M. portae-ferreae* accounted for most of the silica-scaled chrysophytes. *Mallomonas akrokomos* was observed to be a dominant or subdominant species and accounted for a minimum of 0.6% (July 28) to a maximum of 53.1% (December 14) of the cell density of the phytoplankton community (Fig. 6).

A large population of *M. akrokomos* was present throughout the study period and *M. portae-ferreae* was relatively abundant in February and March. Only a few cells of *M. heterospina*, *M. caudata* and *Synura petersenii* f. *petersenii* were observed on a few sampling days and only a few scales of other species were observed during the study period.

The seasonal changes of the *M. akrokomos* population varied between a minimum of 3 cells/ml and a maximum of 347 cells/ml. The peak of *M. akrokomos*

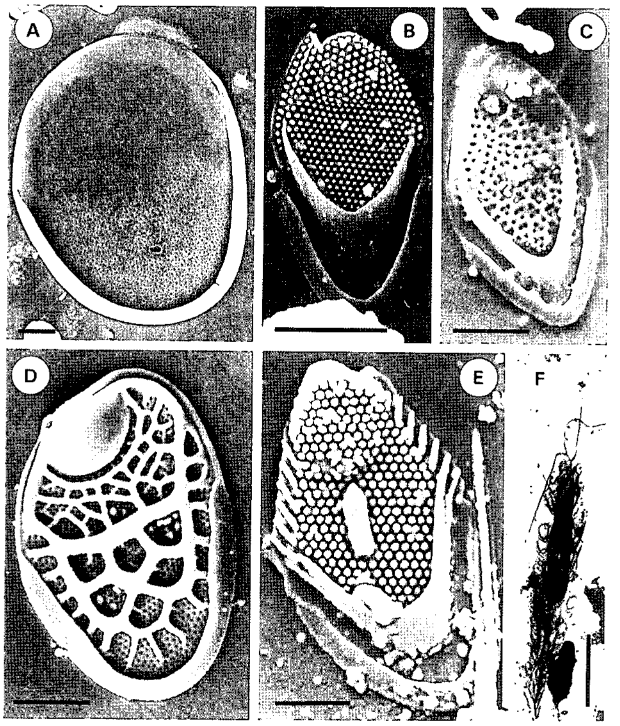

Fig. 1. Scanning electron micrographs of *Mallomonas caudata* (A), *M. paxillata* (B), *M. tonsurata* (C), *M. heterospina* (D), *M papillosa* var. *papillosa* (E), *M. akrokomos* (F). Scale bars = 1 μm (A-E) and 10 μm (F).

appeared on December 14, 1998 and secondary peaks were observed on November 24, 1998 and May 27, 1999. The population density was very low during October and June when the water temperature exceeded 21℃ (Fig. 6A). The population density of *M. akrokomos* fluctuated at 1-2 month intervals between 5℃ and 20℃. However, the population of *M. portae-ferreae* reached maximum density (37 cells/ml) on March 4, 1999, which was relatively high during February and March, 1999 (Fig. 6B).

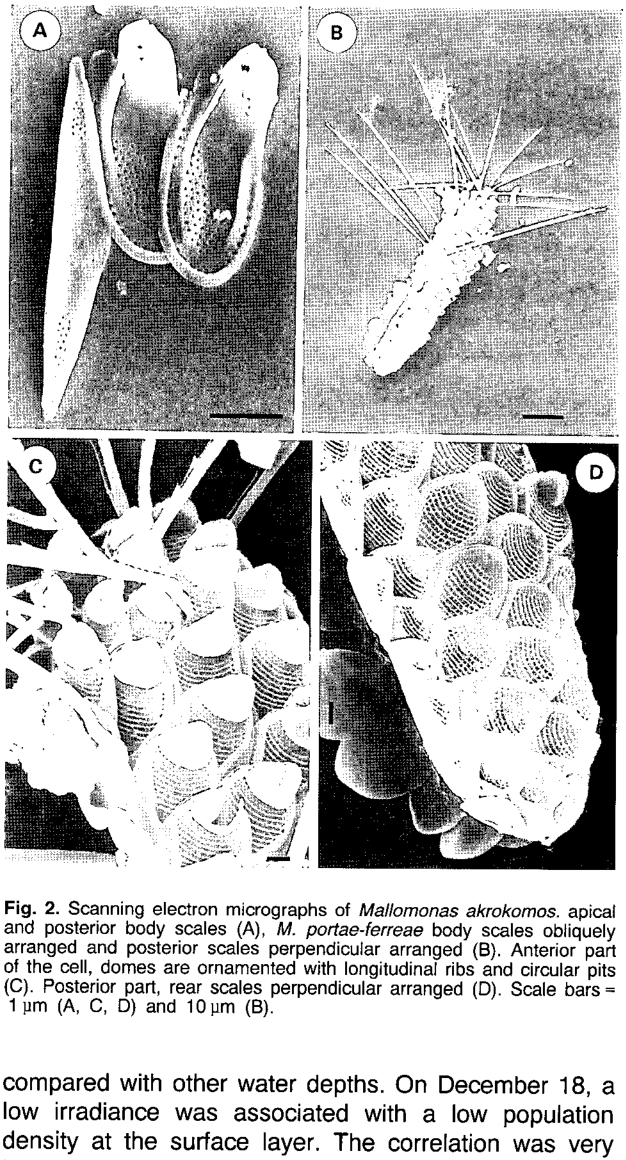

Fig. 2. Scanning electron micrographs of *Mallomonas akrokomos*. apical and posterior body scales (A), *M. portae-ferreae* body scales obliquely arranged and posterior scales perpendicular arranged (B). Anterior part of the cell, domes are ornamented with longitudinal ribs and circular pits (C). Posterior part, rear scales perpendicular arranged (D). Scale bars = 1 μm (A, C, D) and 10 μm (B).

The maximum population density of *M. akrokomos* was observed at different depths according to sampling time but its diurnal vertical distribution showed similar pattern between the two study periods. The diurnal vertical distribution of *M. akrokomos* suggested an upward migration in the morning and a clear downward migration to the bottom in the evening and at night; in general it was evenly distributed throughout the water column except in the surface layer during the day (Fig. 7). The vertical distribution of *M. akrokomos* during the day showed a variable pattern according to the season. On some sampling days, the density of *M. akrokomos* was very low in surface water, when a sub-surface peak was found. Generally, however, *M. akrokomos* was evenly distributed throughout the water column below a water depth of 1 m (Fig. 8). On November 25 and December 29, high irradiance was associated with a very low density in the surface layer, but on January 13 and February 10 and 25, similar light intensities were observed with a high density in the surface layer compared with other water depths. On December 18, a low irradiance was associated with a low population density at the surface layer. The correlation was very low between the seasonal changes of cell density of *M. akrokomos* and physico-chemical and biological factors (r = -0.03–0.38, $P < 0.05$). The vertical distribution of *M. akrokomos* showed relatively strong negative or positive correlations with *Daphnia* density (r = -0.43–-0.74, $P < 0.05$), water temperature (r = -0.73–-0.90, $P < 0.05$) and pH (r = -0.51–-0.81, $P < 0.05$), but showed very low correlations between the vertical distribution of *M. akrokomos* and other physico-chemical and biological factors (Table 2).

Seasonal changes and vertical distribution of ciliata and zooplankton

The most common zooplankton were the rotifer *Polyarthra*, the cladocera *Daphnia*, the calanoid copepod *Acanthodiatomus* and calanoid nauplii (Figs. 4, 5). The density of zooplankton rapidly declined after its maximum density on November 11, 1998; very low density

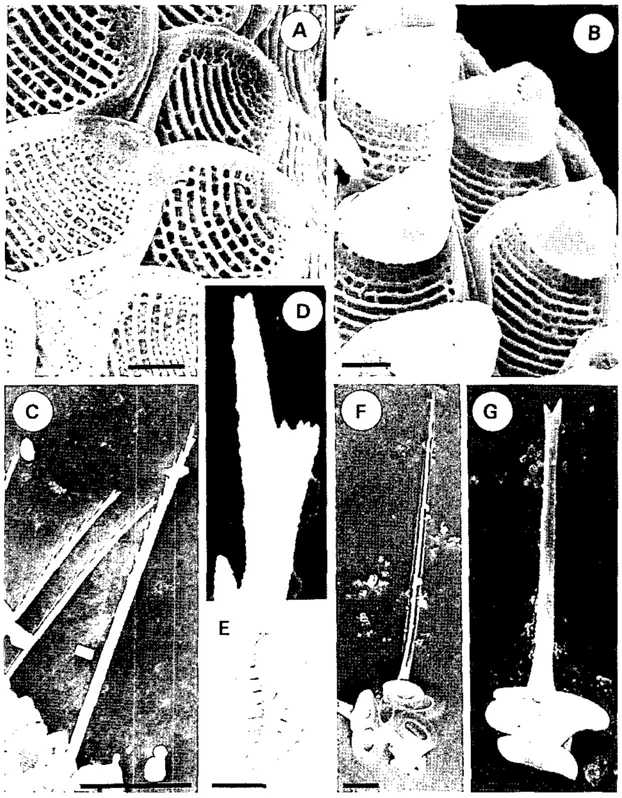

Fig. 3. Scanning electron micrographs of *Mallomonas portae-ferreae*. Posterior scales have a row of teeth at the distal margin and anterior submarginal rib (A). Domes with circular pits, along with a concave margin (B). Shorter apical bristle and longer body bristle (C). Tip of longer bristle with 5 teeth and bifurcated teeth (D). *Synura petersenii* f. *petersenii* (E). *Spiniferomonas trioralis* (F). *Chrysosphaerella brevispina* (G). Scale bars = 1 μm.

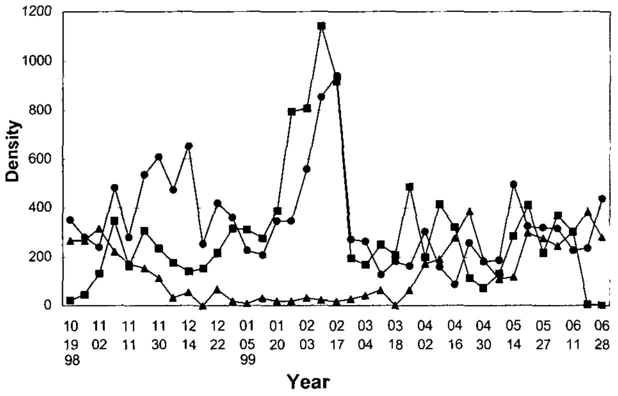

Fig. 4. Seasonal variation of the phytoplankton (●, cells/ml), zooplankton (▲) and ciliata (■, individuals/l) density during the study from October 1998 to July 1999.

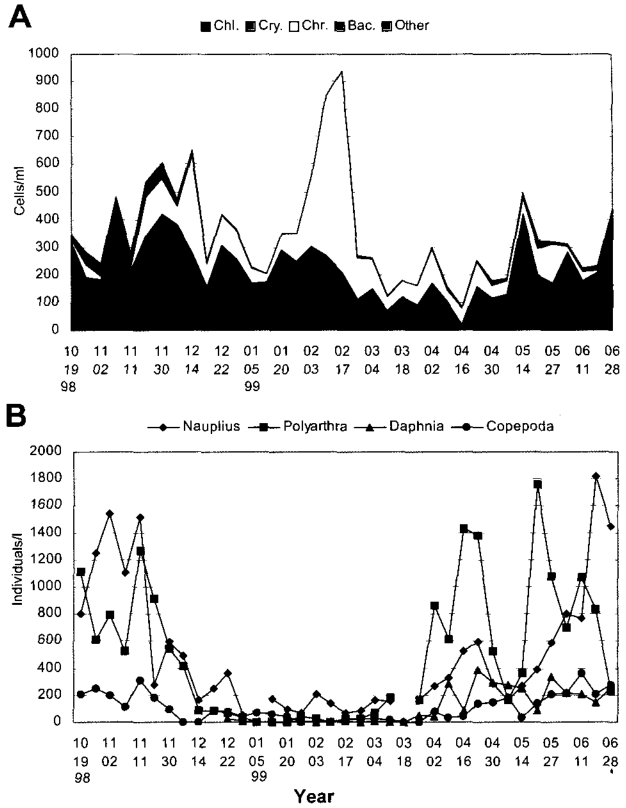

Fig. 5. Seasonal variation of standing crops of main agal groups (A) and zooplankton (B) during the study from October 1998 to July 1999 (Chl: Chlorophyceae, Cry: Cryptophyceae, Chr: Chrysophytes, Bac: Bacillariophyceae).

was maintained from December, 1998 to March, 1999 and high density continued from April to July, 1999. In general, diurnal vertical distributions of zooplankton showed maximum density at the bottom but at 05:00 on the first sampling and at 14:00 and 17:00 of the second sampling showed its maximum density at the surface and 2 m depth, respectively (Fig. 9). The population of ciliata showed maximum density on February 10 and minimum density on October 19. There was a tendency for ciliates to accumulate at sub-surface depths between 1 and 3 m (Figs. 4, 9).

Discussion

Ten taxa of silica-scaled chrysophytes were found in the present study. Most of the species except for *M. paxillata* and *M. portae-ferreae,* which have worldwide distribution but occur in very low density (Takahashi, 1978; Dürrschmidt, 1982; Hartmann & Christiansen, 1989; Péterfi et al., 1998), are reported among the most common and widespread species of the scaled chrysophytes (Takahashi, 1978; Dürrschmidt, 1980; Nicholls, 1982; Wee, 1982; Kling & Kristiansen, 1983; Cronberg, 1989; Siver, 1991). However, in the present study, only a few scales or very low densities were observed for most of these species.

Mallomonas akrokomos is the most common and widely distributed species in Japan as well as worldwide (Takahashi, 1978; Siver, 1991). Although Harris (1958), Takahashi (1978) and Siver (1991) reported that this eurythermal species appears throughout the year, they reported that it prefers cold water below 6℃

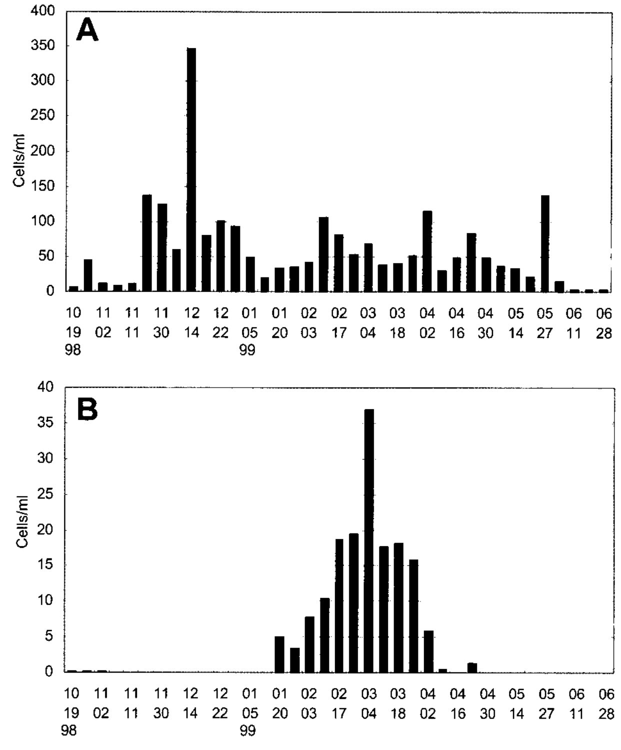

Fig. 6. Seasonal variation of population density of *Mallomonas akrokomos* (A) and *M. portae-ferreae* (B) during the study from October 1998 to July 1999.

and has a maximum in the winter-spring season. Also, Dürrschmidt (1984), Siver and Chock (1986), Ito (1988) and Kristiansen (1985, 1988) reported a winter-spring maximum for this species, and Takahashi (1978) reported that its maximum population appeared at about 4℃ in water temperature and occurred from October to February in Japan. However, Roijackers and Kessels (1986) reported that it may have two maxima, one at between 4-10℃ and the other at 18-20℃. The result of this study, the seasonality of *M. akrokomos* with peaks during November and December at 6.8-10.1℃ and in May (20.5℃) was similar to the report of Roijackers and Kessels (1986). However, additional peaks in population density appeared at 1-2 months intervals during the survey period between these temperature ranges. *Mallomonas portae-ferreae* has been recorded worldwide, but it is a very rare species for which loose scales only had previously been reported in Japan (Ito, 1988). In this investigation, a large popu- lation of *M. portae-ferreae* was observed during February and March. This species was reported to be alkaliphilous and mainly appeared in autumn and spring (Kristiansen, 1981; Gretz et al., 1985; Ito, 1988), and Siver and Hamer (1989, 1992) reported that water temperature, pH and conductivity were important factors in controlling the occurrence of this species. Also, Siver (1995) reported that this species is a taxon that began growth in the summer, persisted through the autumn and disappeared in the winter. Cronberg (1989) and Péterfi and Momeu (1996) reported that *M. portae- ferreae* is mostly found in tropical and subtropical regions and its occurrence is limited to the warm season of the year in temperate zones. However, a quantitative examination of the occurrence of this species was not attempted previously. In the present study, *M. portae-ferreae* was shown to have a maxi- mum density in early spring, apparently preferring low temperatures between 5.3-10.1℃; its density was very low above 15℃ and it disappeared after May.

Many works on the vertical distribution and diurnal migration of flagellated organisms exist (Reynolds, 1984; Sandgren, 1988). Vertical migrations of some species may be affected by environmental conditions (Heaney & Talling, 1980). Only a few studies on the vertical distribution of *Mallomonas* species have been carried out (Nygaard, 1977; Croome & Tyler, 1988; Jones, 1988; Hoffmann & Wille, 1992). Maulood et al. (1978) reported maximum density of *Mallomonas* species at the surface during the day and Jones (1988) reported that maximum occurrence of *M. akrokomos* appeared in the surface and subsurface (water depth 1 m) layers and that it migrated to the surface layer with increasing solar irradiation after sunrise. However, most of species previously studied

Table 2. Correlation coefficents between the seasonal changes (A) and vertical distributions (B) of cell density of *Mallomonas akrokomos* and variable factors

A (n = 36)

Chl	Cry	Bac	Cil	Nau	Pol	Dap	Cop	WT	pH	DO	NO_2-N	NO_3-N	NH_4-N	TN	PO_4-P	TP
-0.20	0.29	0.16	0.03	-0.38	-0.17	-0.09	-0.32	-0.37	-0.13	0.37	-0.09	0.19	0.27	0.27	0.03	0.23

B (n = 20)

Depth	Cil	Nau	Pol	Dap	Cop	Light	WT	pH	DO	NO_2-N	NO_3-N	NH_4-N	TN	PO_4-P	TP
0 m	-0.50	-0.10	0.16	-0.58	-0.45	-0.05	-0.78	-0.51	0.32	0.29	0.34	0.12	0.20	-0.17	0.66
1 m	-0.75	-0.15	-0.48	-0.73	-0.41	-0.05	-0.88	-0.75	-0.14	0.35	0.62	0.48	0.54	-0.27	0.34
2 m	-0.20	0.30	-0.33	-0.43	-0.01	-0.07	-0.77	-0.81	0.20	0.02	0.51	0.46	0.45	-0.02	0.32
3 m	-0.21	0.58	-0.65	-0.74	-0.38	-0.05	-0.90	-0.71	-0.44	0.19	0.45	0.50	0.50	0.01	0.51
4 m	0.21	0.15	0.10	0.05	0.07	-0.10	-0.73	-0.74	-0.33	0.32	0.38	0.51	0.47	-0.11	-0.19

Chl: Chlorophyceae, Cry: Cryptophyceae, Bac: Bacillariophyceae, Nau: Nauplius, Dap: *Daphnia*, Pol: *Polyarthra*, Cop: Copepoda, WT: Water temperature, DO: Dossolved oxygen, NO_2-N: Nitrite, NO_3-N: Nitrate, NH_4-N: Ammonium, TN: Total nitrogen, PO_4-P: Phosphate, TP: Total phosphorus.

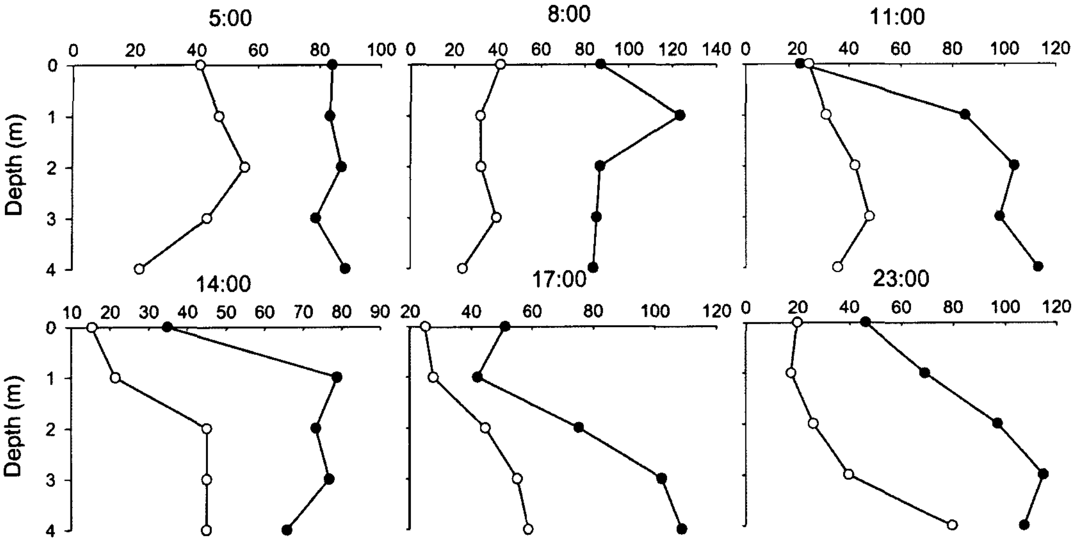

Fig. 7. Diurnal vertical distributions of *Mallomonas akrokomos* at six times on two dates (cells/ml).

were reported as a shade plankton attaining their largest densities in the metalimnion, hypolimnion or below surface of 2 and 3 m.

In the present study, the vertical distribution of *M. akrokomos* supports most of the previous reports that *Mallomonas* species may be a shade plankton with maximum densities below sub-surface layer. We have also confirmed a part of the diurnal migration pattern reported by Jones (1988) and Croome and Tyler (1988) in that *M. akrokomos* migrates downward in the evening in response to decreased irradiance and upward in the morning in response to increasing irradiance, but we did not clearly demonstrate upward migration to the surface in the morning. The diurnal vertical distribution and migration of flagellate phytoplankton may be a direct response to changing light intensity, temperature, nutrient condition and a complex interaction among these factors (Heaney & Talling, 1980; Heaney & Epply, 1981; Salonen et al., 1984). Also, the vertical distribution of flagellate phytoplankton may be affected by herbivore grazing (Lehman & Sandgren, 1985; Arvola et al., 1987). In this study,

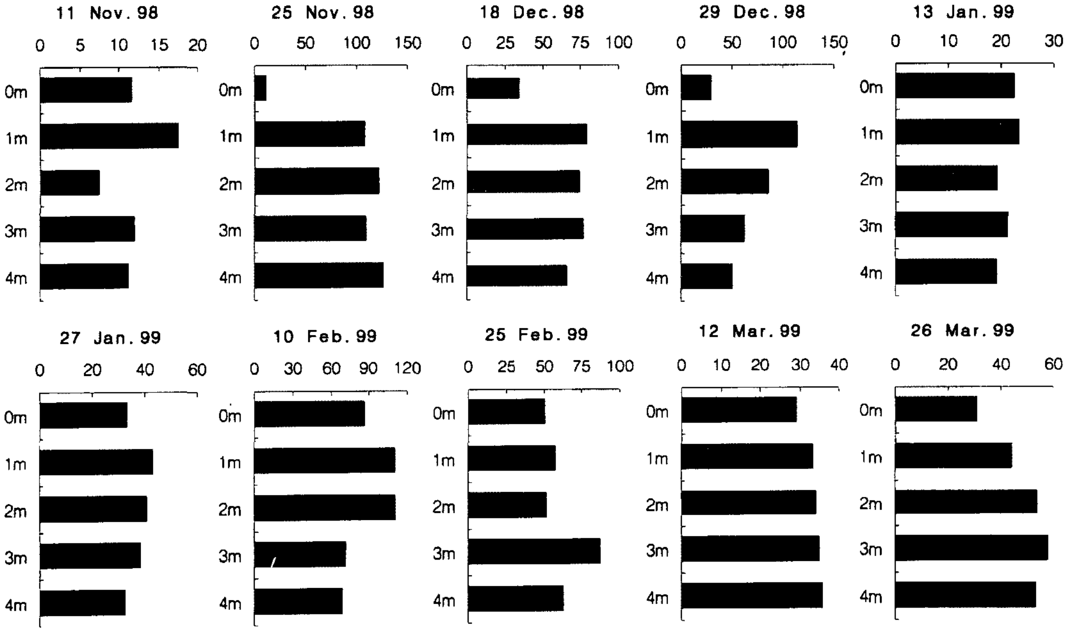

Fig. 8. Vertical distributions of *Mallomonas akrokomos* (cells/ml) during the study.

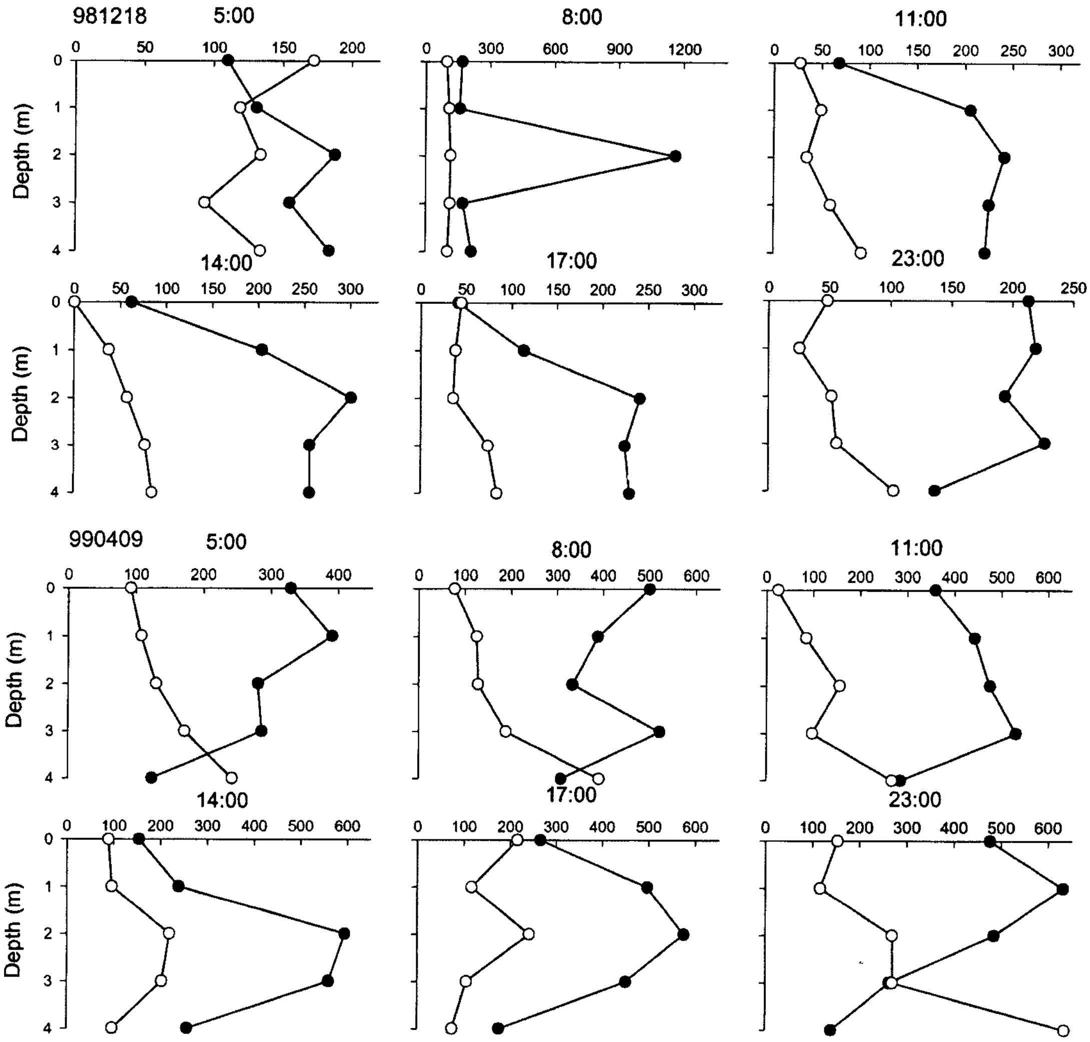

Fig. 9. Diurnal vertical distributions of the ciliata and total zooplankton density (individuals/l) during the study.

diurnal vertical distribution of *M. akrokomos* did show negative correlations with zooplankton, light intensity, water temperature and pH, and a positive correlation with nutrient conditions. Although the vertical distribution of *M. akrokomos* showed significant correlations with water temperature, pH and *Daphnia*, it did not show significant correlations with the other surveyed zooplankton and physico-chemical factors. A complex interaction among physico-chemical and biological factors seemed to affect the vertical distribution of *M. akrokomos*. However, the vertical distribution of flagellate phytoplankton may be affected by their horizontal patchness (Jones, 1988), and may be controlled by endogenous rhythms (Heaney & Furnass, 1980; Frempong, 1981). Thus, future studies need to consider horizontal gradients, and more frequent sampling is necessary to better understand the diurnal vertical distribution pattern of *M. akrokomos*.

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References

APHA (1992) Standard Methods for the Examination of Water and Wastewater, 18th Ed. Americal Public Health Association, Washington D.C.

Arvola L (1986) Spring phytoplankton of 54 small lakes in southern Finland. *Hydrobiology* 137: 125-134.

Arvola L, Salonen K, Hones RI, Heinanen A, and Bergstrom I (1987) A three day study of the diel behaviour of plankton in a highly humic and steeply stratified lake. *Arch Hydrobiol* 109: 89-106.

Clasen J and Bernhardt H (1982) A bloom of the Chrysophyceae *Synura uvella* in the Wahnbach reservoir as indicator for the release of phosphates from the sediment. *Arch Hydrobiol Beih* 18: 61-68.

Cronberg G (1989) Scaled Chrysophytes from the tropics. *Beih*

Nova Hedwigia 95: 191-232.

Croome RL and Tyler PA (1988) Phytoflagellates and their ecology in Tasmanian polyhumic lakes. *Hydrobiology* 161: 245-253.

Dürrschmidt M (1980) Studies on the Chrysophyceae from Rio Cruces, Prov. Valdivia, south Chile by scanning and transmission electron microscopy. *Nova Hedwigia* 33: 353-388.

Dürrschmidt M (1982) Studies on the Chrysophyceae from South Chilean inland waters by means of scanning and transmission electron microscopy, II. *Arch Hydrobiol* Suppl 63: 121-163.

Dürrschmidt M (1984): Studies on scale-bearing Chrysophyceae from the Giessen area, Federal Republic of Germany. *Nord J Bot* 4: 123-143.

Eloranta P (1989) Scaled chrysophytes (Chrysophyceae and Synurophyceae) from national park lakes in southern and central Finland. *Nord J Bot* 8: 671-681.

Frempong E (1981) Diel variation in the abundance, vertical distribution and species composition of phytoplankton in a eutrophic English lake. *J Ecol* 69: 919-939.

Gretz, MR, Sommerfeld MR, and Wujek DE (1985) Light and electron microscopical observations of *Mallomonas portae-ferreae* var. *reticulata* var. nov. (Chrysophyceae). *Phycologia* 24: 478-481.

Harris K (1958) A study of *Mallomonas insignis* and *Mallomonas akrokomos*. *J Gen Microbiol* 19: 55-64.

Hartmann H and Chrystiansen S (1989) The occurrence of silica-scaled chrysophytes in some central European lakes and their relation to pH. *Nova Hedwigia* 95: 131-158.

Heaney SI and Eppley RW (1981) Light, temperature and nitrogen as interacting factors affecting diel vertical migrations of dinoflagellates in culture. *J Plankton Res* 3: 331-344.

Heaney SI and Furnass TI (1980) Laboratory models of diel vertical migration in the dinoflagellate *Ceratium hirundinella*. *Freshwater Biol* 10: 163-179.

Heaney SI and Talling JF (1980) Dynamic aspects of dinoflagellate distribution patterns in a small, productive lake. *J Ecol* 68: 75-94.

Hoffmann L and Wille E (1992) Occurrence of a metalimnetic summer peak of *Mallomonas caudata* (Synurophyceae). *Nord. J Bot* 12: 465-469.

Iwakuma T, Shibata K, and Hanazato T (1989) Production ecology of phyto- and zooplankton in a eutrophic pond dominated by *Chaoborus flavicans* (Diptera : Chaobolidae). *Ecol Res* 4: 31-53.

Ito H (1988) Scale-bearing chrysophytes in the south basin of lake Biwa, Japan. *J Phycol* 36: 143-153.

Jones RI (1988) Vertical distribution and diel migration of flagellated phytoplankton in a small humic lake. *Hydrobiology* 161: 75-87.

Kling HJ and Kristiansen J (1983) Scale-bearing Chrysophyceae (Mallomonadaceae) from central and nothern Canada. *Nord J Bot* 5: 381-398.

Kristiansen J (1975) Chrysophyceae from Alberta and British Columbia. *Syesis* 8: 97-108.

Kristiansen J (1981) Distribution problems in the Synurophyceae (Chrysophyceae). *Verh Int Ver Limnol* 21: 1444-1448.

Kristiansen J (1985) Occurrence of scale-bearing Chrysophyceae in eutrophic Danish Lake. *Verh Int Ver Limnol* 22: 2826-2829.

Kristiansen J (1986) Identification, ecology, and distribution of silica scale-bearing Chrysophyceae, a critical approach. In: Kristiansen J, and Andersen RA (eds.): Chrysophyte: Aspects and Problems, Cambridge University Press, New York, pp 229-239.

Kristiansen J (1988) Seasonal occurrence of silica-scaled Chrysophyceae under eutrophic conditions. *Hydrobiology* 161: 171-184.

Kristiansen J and Takahashi E (1982) Chrysophyceae: introduction and bibliography. In: Rosowski J, and Parker B (eds.) Selected Papers in Phycology, Vol. 2. Phycological Society of America, Lawrence, pp 698-704.

Lehman JT and Sandgren CD (1985) Species-specific rate of growth and grazing loss among freshwater algae. *Limnol Oceanogr* 30: 34-46.

Maulood BK, Hinton GCF, and Boney AD (1978) Diurnal variation of phytoplankton in Loch Lomond. *Hydrobiology* 58: 99-117.

Nicholls KH (1982) *Mallomonas* species (Chrysophyceae) from Ontario, Canada including descriptions of two new species. *Nova Hedwigia* 34: 80-124.

Nygaard G (1977) Vertical and seasonal distribution of some motile freshwater plankton algae in relation to some environtmental factors. *Arch Hydrobiol* Suppl 51: 67-76.

Peterfi LS and Momeu L (1996) Three Rumanian *Mallomonas* species (Synurophyceae), with special distribution patterns. *Hydrobiology* 336: 143-150.

Péterfi LS, Momeu L, Padisák J, and Varga V (1998) Silica-scaled chrysophytes from permanent and temporary waters of Hortobágy, eastern Hungary. *Hydrobiology* 369/370: 339-351.

Pick RF and Nalewajko C (1984) The origin of a metalimnetic phytoplankton peak. *Limnol Oceanogr* 29: 124-134.

Reynolds CS (1984) The Ecology of Freshwater Phytoplankton. Cambridge University Press, Cambridge.

Roijackers RMM, and Kessels H (1986) Ecological characteristics of scale-bearing Chrysophyceae from the Netherlands. *Nord J. Bot* 6: 373-383.

Saha LC and Wujek DE (1990) Scale-bearing chrysophytes from tropical Northeast India. *Nord J. Bot* 10: 343-354.

Salonen K, Jones RI, and Arvola L (1984) Hypolimnetic phosphorous retrived by diel vertical migrations of lake phytoplankton. *Freshwater Biol* 14: 431-438.

Sandgren CD (1988) The ecology of chrysophyte flagellates: their growth and perennation strategies as freshwater phytoplankton. In: Sandgren CD (ed.), Growth and Reproductive Strategies of Freshwater Phytoplankton. Cambridge University Press, Cambridge, pp 9-104.

Siver PA (1991) The Biology of *Mallomonas*: Morphology, Taxonomy and Ecology. Kluwer Academic Publlisher Dordrecht.

Siver PA (1995) Distribution of chrysophytes along environmental gradients. In: Sandgren CD, Smol JP, and Kristiansen J (eds.), Chrysophyte Algae. Cambridge University Press, Cambridge, pp 232-268.

Siver PA and Chock JS (1986) Phytoplankton dynamics in a chrysophycean lake. In: Kristiansen J, and Andersen RA (eds.). Chrysophytes: Aspects and Problems. Cambridge University Press, Cambridge, pp 165-183.

Siver PA and Hamer JS (1989) Multivariate statistical analysis of the factors controlling the distribution of scaled chrysophytes. *Limnol Oceanogr* 34: 368-381.

Siver PA and Hamer JS (1992) Seasonal periodicity of chrysophyceae and synurophyceae in a small New England lake: implications for paleolimnological research. *J Phycol* 28: 186-198.

Takahashi E (1978) Electron Microscopical Studies of the Synuraceae (Chrysophyceae) in Japan: Taxonomy and Ecology. Tokai University Press, Tokyo.

Utermöhl H (1958) Zur Vervollkommnung der quantitativen Phytoplankton-Methodik. *Mitt Int Verein Theor Angew Limnol* 9: 39.

Wee JL (1982) Studies on the Synuraceae (Chrysophyceae) of Iowa. *Bibl Phycol* 62: 1-183.

Xie P, Iwakuma T, and Fujii K (1998a) Studies on the biology of *Chaoborus flavicans* (Meigen) (Diptera: Chaoboridae) in a fish-free eutrophic pond, Japan. *Hydrobiology* 368: 83-90.

Xie P, Iwakuma T, and Fujii K (1998b) Changes in the structure of a zooplankton community during a *Ceratium* (dinoflagellate) bloom in a eutrophic fishless pond. *J Plankton Res* 20: 1663-1678.

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