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Author(s)	Terasaki, Emi; Morita, Kou; Yasuda, Masaomi; Maekawa, Kimihiko; Montani, Shigeru
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Spatial distribution of phytopigments and organic matter in surface sediments in Lake Saroma (Hokkaido, Japan)

Emi TERASAKI[1),*], Kou MORITA[2)], Masaomi YASUDA[3)],
Kimihiko MAEKAWA[4)] and Shigeru MONTANI[1)]

Abstract : In Lake Saroma, scallops have been adversely affected by hypoxic events, which are caused by long-term scallop culture in summer. In this study, we were conducive to the spatial distribution of Chl *a*, phaeopigment, total organic carbon (TOC) and total nitrogen on a grid of 54 stations in surface sediments. The temporal changes in the TOC content of the surface sediments since the initiation of scallop culture in Lake Saroma were also studied. The average Chl *a* /total pigments was 0.7±0.2 in the organic poor area (PA), which was higher than 0.4 ± 0.2 in the organic rich area (RA). Benthic environments were suited for growing microphytobenthos in the PA. In contrast, the RA has become increasingly eutrophic because of the average TOC was 23±5 mg g^{-1}, which was higher than 6±3 mg g^{-1} in the PA. During the past 40 years, after the TOC content had decreased in surface sediment owing to the excavation work, it has increased in the RA owing to the concentrated scallop culture facilities. This study concludes that benthic environments in Lake Saroma are directly and indirectly affected by human activities, particularly in the RA.

Keywords : *Sediments, Scallop culture, Phytopigment, Organic matter*

1. Introduction

Coastal lagoons are rich in nitrogen and phosphorus compounds and provide highly productive habitats for aquatic life such as fish and shellfish. Coastal lagoons are often used for aquaculture activities, which may have direct or indirect environmental impacts, primarily because of the excessive inputs of nutrients and organic matter. Riverine inflows and the transport of allochthonous particles and organic matter also affect the physicochemical environments of lagoons, which widely fluctuate at the interface between freshwater and seawater (MEADE, 1972; ALLEN *et al.*, 1980). The large supply of organic matter derived from aquaculture and riverine inputs into coastal lagoons often cause hypoxic or anoxic events that lead to fish and benthic mortalities (GOWEN *et al.*, 1991; PEARSON and BLACK, 2001), thereby affecting aquacultural activities. Therefore, investigating the depositional environment to assess the characteristics of benthic environments could facilitate better management practices.

The organic matter in surface sediments is an important source of food for benthic fauna. However, overabundance may lead to benthic

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1) Graduate school of Environmental Science, Hokkaido University, N10W5 Kita-ku, Sapporo, Hokkaido 060-0810, Japan
2) Hokkaido Aquaculture Promotion Corporation, 1-3-3 Yonesato 4 jo, Siroishi-ku, Sapparo, Hokkaido 003-0874, Japan
3) Tohoku Electric Power Company, Incorporated, 1-7-1 Hon-chou, aoba-ku, Sendai, Miyagi 980-8550, Japan
4) Aquaculture Fishery Cooperative of Saroma Lake, Sakaeura, Tokoro, Kitami, Hokkaido 093-0216, Japan
* Corresponding author: Address: Graduate school of Environmental Science, Hokkaido University, N10W5 Kita-ku, Sapporo, Hokkaido 060-0810, Japan. Tel.: +81 11 706 2322.
E-mail: hamulin@ees.hokudai.ac.jp (E. Terasaki)

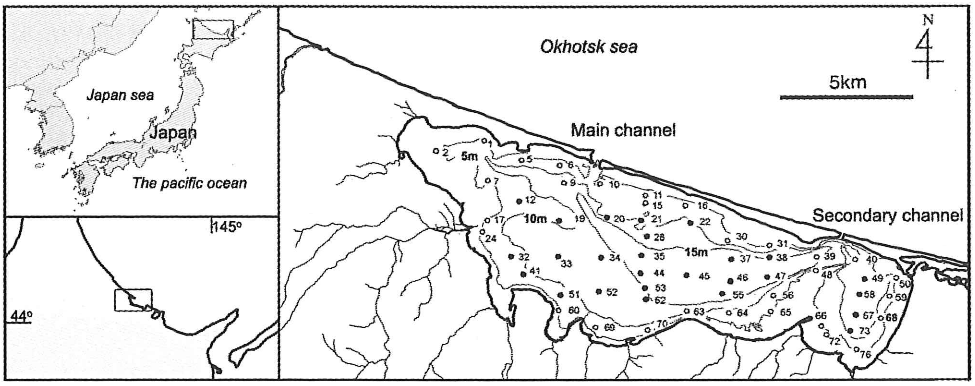

Fig. 1. The study area and sampling stations in Lake Saroma, Hokkaido, Japan. ●: In the scallop culture facility.

impairment due to oxygen depletion and build-up of toxic byproducts, associated with the breakdown of these materials (Hyland *et al.*, 2005; Magni *et al.*, 2009). The negative effects of excessive loads of organics are known to be related to the hydrodynamic features of lagoons (Tagliapietra *et al.*, 2012). In the Lake Saroma, the scallop culture has an area of 80 km^2 or 53% of the total area and has been conducted since 1960ies, achieving a maximum production of 9000 tons in 1979. However, water quality problems such as red tide occurred, affecting scallop production that decreased to 3700 tons in 1985. Thus, a fisherman's association tried to be rebounded scallop production from the impact of water pollution by interim downturn amount of scallop culture. Additionally, it was prompted the digging of a secondary channel to improve water flow. Then, scallop production rebounded to 6,700 tons in the 1990ies and was an advantage of 6,000 tons per year at present. However, in the summer of 1987 dissolved oxygen concentration decreased to 30% in the lake below a depth of 15 m (Sampei *et al.*, 1997). Recently, hypoxic events are caused by the excessive input of organic matters from rivers and long-term scallop culture facilities. Several benthic environmental studies have been conducted in Lake Saroma (Satake, 1967; Kikuchi *et al.*, 1984; Nishihama and Hoshikawa, 1992; Kashima, 1996; Sampei *et al.*, 1997; Sonoda *et al.*, 2002; Katsuki *et al.*, 2009). These studies suggested that benthic environments are influenced by scallop culture and that surface sediments are partly eutrophic. However, no statistical studies have been conducted to analyze sediment eutrophication and temporal changes in the TOC content of sediments since the initiation of scallop culture in Lake Saroma. Additionally, no study reported phytopigments contents as basic biochemical parameter in surface sediment. Phytopigments were important information because these gave an indicative of primary producer and a source of feed for filter feeder. Spatial distributions of phytopigments were necessary data to assess the impact of scallops to surface sediment because biodeposition of scallops included phytopigments. In this study, the primary goals were (i) to understand spatial distribution of phytopigments and organic matter and to assess these levels and statistically the eutrophic sediments area of Lake Saroma; and (ii) to see if there is any relationship between temporal changes in the TOC content of sediment to human activities since the initiation of scallop culture in Lake Saroma.

2. Materials and Methods

Study site

Lake Saroma is located in the subarctic zone of Japan and it is connected with the Sea of Okhotsk by a westward main channel and an eastward secondary channel (Fig. 1). It is the largest coastal lagoon in Japan with an area of 150 km^2, an average depth of 9 m, and a maximum depth of about 20 m (KIKUCHI *et al.*, 1984; NISHIHAMA and HOSHIKAWA, 1992; KATSUKI *et al.*, 2009). Furthermore, ring current at high tide currents mainly toward south from the main channel and partly circulated at west end and Kimuaneppu cape in Lake Saroma (SATAKE, 1967). Other ring current at high tide currents plume-form from the secondary channel after that linearly current, in contrast ring currents at low tide were reverse (HAGINO, 1985). Flow volume at the mainly and the secondary channels were able to calculate from tidal range between the open seawater. Order of flow volume at the mainly and the secondary channels were 10^8 m^3 and 10^7 m^3 per one-tide, respectively and the ratio was about 9 : 1 (TAKEUCHI *et al.*, 1990).

Field surveys

Sampling was conducted using a grid at 56 stations on September 26, 2005 (Fig. 1). Surface (0–1 cm) sediment samples were collected at each station using Ekman-Birge type bottom sampler (15 cm × 15 cm). The samples were packed in zipper bags and stored in a refrigerator. After returning to the laboratory, the samples were stored at −20°C until analysis after removing the pore water by centrifugation (3,000 rpm for 10 min).

The present study was conducted following a hypoxic event in September 2005. During this year, Lake Saroma was characterized by high biological productivity and high biodeposition (KURATA *et al.*, 1991). In our survey, we also found that the chlorophyll-*a* (Chl *a*) concentration and primary production in the water column were as high as 3.2 $\mu g\ l^{-1}$ and 1 $g\ C\ m^{-2}\ day^{-1}$, respectively (unpublished data).

Sediment analysis

To determine the Chl *a* and phaeopigment contents of the sediments, about 0.1 g of the sediment sample was added to a test tube and Chl *a* and phaeopigment were extracted using 90% acetone. The test tube was then placed in a freezer in dark conditions at −20°C for one day. After ultrasonication for five minutes, the concentration of Chl *a* in the supernatant of the test tube was determined using a fluorophotometer (Turner 10-AU-5, Turner Designs), according to LORENZEN's (1967) method as described by PARSONS *et al.* (1984).

To determine the organic carbon and nitrogen content in the sediments, samples were freeze-dried and ground to a powder using a mortar. Prior to the analysis, the samples were treated with 1N HCl to remove any traces of inorganic carbon, rinsed with deionized and distilled water to remove the acid, and freeze-dried. The total organic carbon (TOC) and total nitrogen (TN) content were determined using a CHN analyzer (NA–1500, Fusion Designs).

Data analysis

Cluster analysis and multidimensional scaling (MDS) were conducted to understand the sedimentary environment in Lake Saroma depending on the sources of the organic matter. Cluster analysis (Ward's method) was conducted using a Euclidean distance technique for the TOC, TN, and Chl *a*/total (Chl *a* + phaeopigment) pigments (Chl *a*/total) ratio content to categorize the sediments. The MDS ordination analysis was performed using a Euclidean distance technique with the same data to produce a two-dimensional (2D) plot of the categorized sediments.

3. Results

Sediment characteristics

The average Chl *a* and phaeopigment contents for all analyzed stations were 73 ± 86 $\mu g\ g^{-1}$ and 94 ± 142 $\mu g\ g^{-1}$, respectively. The Chl *a* content exhibited a distribution similar to that of the phaeopigment content, except at Stn. 68, where the Chl *a* content (155 $\mu g\ g^{-1}$) differed from the phaeopigment content (25 $\mu g\ g^{-1}$) [Figs. 2 (a) and (b)]. The Chl *a* content was greater than 200 $\mu g\ g^{-1}$ at westernmost side in Stns. 1, 2, and 72, while it was about 10 $\mu g\ g^{-1}$ at mainly seaside in Stns. 9, 11, 15, 22, 30, 63, and 70, with a minimum value of 1.4 $\mu g\ g^{-1}$ at Stn.10 [Fig. 2 (a)]. The phaeopigment content was greater than 200 $\mu g\ g^{-1}$ at westernmost side, where the Chl *a* content was high [Fig. 2 (a) and (b)]. In contrast, the phaeopigment content was lesser than 10 $\mu g\ g^{-1}$ at seaside, with a minimum value at and easternmost side in Stns. 48, 59, and 68 [Fig. 2 (b)].

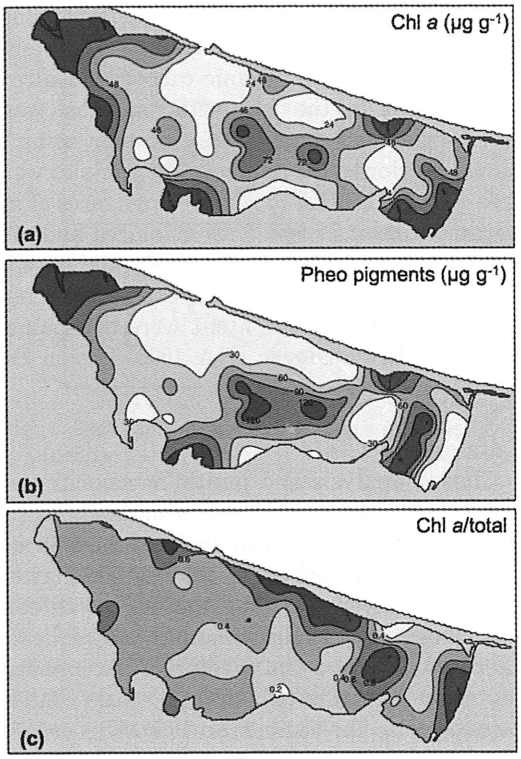

Fig. 2. (a) Spatial distributions of chlorophyll-*a* (Chl *a*) content, (b) special distribution of phaeopigment content, and (c) special distribution Chl *a*/total pigments (Chl *a*/total) ratio in the surface (0–1 cm) sediments of Lake Saroma.

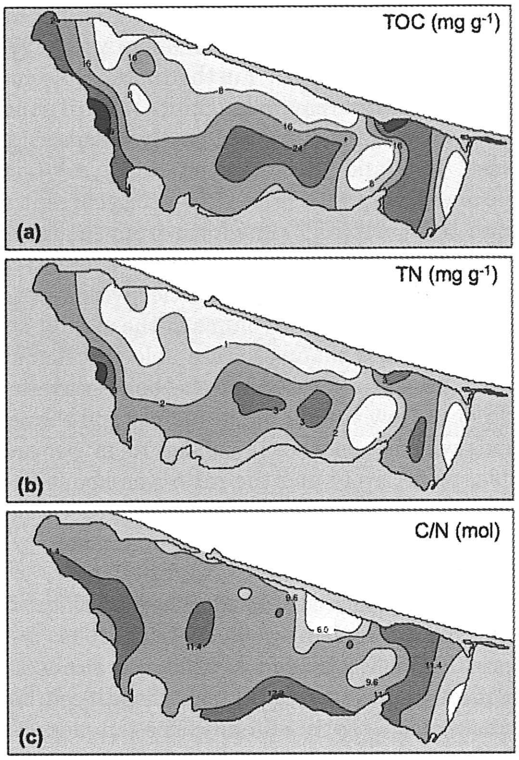

Fig. 3. (a) Spatial distribution of the total organic carbon (TOC) content, (b) special distribution total nitrogen (TN) content, and (c) carbon to nitrogen (molar; C/N) ratio in the surface (0–1 cm) sediments of Lake Saroma.

The distribution of Chl *a*/total pigments exhibited a better agreement with bathymetry than those of Chl *a* and phaeopigment contents (Fig. 2). The average Chl *a*/total ratio was 0.50 ± 0.18; a high Chl *a*/total ratio was recorded at seaside and easternmost side, with a maximum value of 0.96. In contrast, a low Chl *a*/total ratio was recorded at Stns. 39, 63, and 67, with a minimum value of 0.17 [Fig. 2 (c)].

The TOC and TN distributions exhibited a better agreement with the phaeopigment content than with Chl *a* (Fig. 3). The average TOC and TN contents were 18±12 mg g^{-1} and 2.0± 1.3 mg g^{-1}, respectively. A high TOC content of greater than 30 mg g^{-1} was observed at Stns. 66 and 73, with a maximum value of 38 mg g^{-1} at Stn. 24 [Fig. 3 (a)]. In contrast, a low TOC content was recorded at Stns. 31 and 48, with a minimum value of 1.8 mg g^{-1} at Stn. 10 [Fig. 3 (a)]. A high TN content of greater than 3 mg g^{-1} was observed at depth > 10 m in east basin and > 15 m in west basin, with a maximum value of 4.1 mg g^{-1} at Stn. 24 [Fig. 3 (b)]. In contrast, a low TN content of lesser than 0.5 mg g^{-1} was observed at seaside and easternmost side [Fig. 3 (b)]. The C/N (mol) ratio had an average value of 10±1, whereas it was about 12 near river mouth and the secondary channel [Fig. 3 (c)]. In contrast, a low C/N ratio of 6–8 was observed at seaside and easternmost side, which agreed with the high Chl *a*/total content [Fig. 3 (c)].

Spatial patterns

Using the TOC, TN, and the Chl *a*/total data, the sediment samples were categorized into two

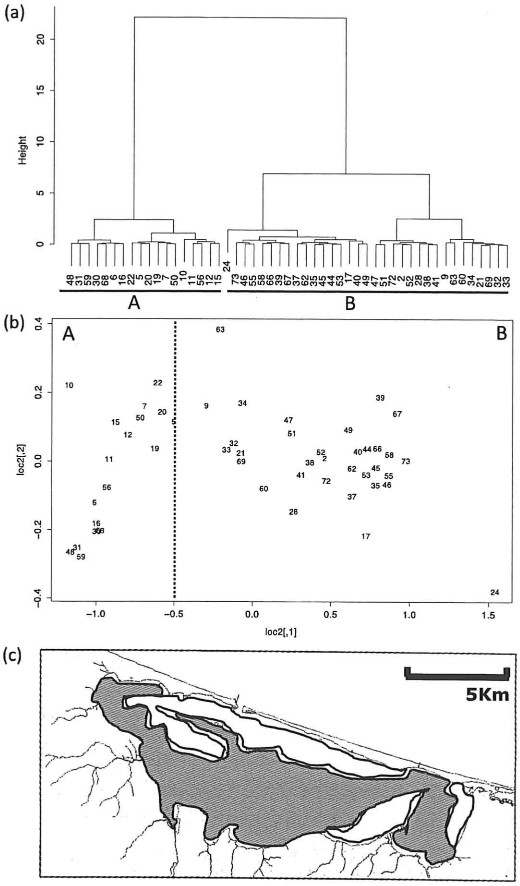

Fig. 4. (a) Dendrogram produced using Ward's clustering method and (b) multidimensional scaling (MDS) ordination plots for total organic carbon (TOC) and total nitrogen (TN) contents and chlorophyll-*a* to total pigments (Chl *a*/total) ratio data of surface sediments from Lake Saroma. Group A: the organic poor area; Group B: the organic rich area. (c) Classification map derived from (a) and (b). □: the organic poor area; ▨: the organic rich area.

main groups (n=51/58). Group A was the organic poor area (PA) that included Stns. 5–7, 10–16, 19–22, 30, 31, 48, 50, 56, 59, 65, and 68 (Fig. 4). Group B was the organic rich area (RA) that included Stns. 1, 2, 9, 17, 21, 24–47, 49, 51–55, 58, 60–64, 66, 67, and 69–76 (Fig. 4). Spatial patterns of PA and RA agreed with the bathymetry and ring currents. The grain size composition for PA was sand and silty sand to clay for RA (NISHIHAMA & HOSHIKAWA, 1992; SAMPEI *et al.*, 1997). The average depths in RA and PA were 13±5 m and 7±3 m, respectively. The scallop culture facilities were located in RA, which were at depth of greater than 10 m. The average Chl *a* and phaeopigment contents were 37±36 μg g^{-1} and 19±20 μg g^{-1}, respectively, in PA, and 91±102 μg g^{-1} and 122±156 μg g^{-1}, respectively, in RA. The average Chl *a*/total ratio was 0.7±0.2 in PA and 0.4±0.2 in RA. The average TOC and TN contents were 6.3±3.1 mg g^{-1} and 0.7±0.3 mg g^{-1} in PA and 23.4±5.4 mg g^{-1} and 2.5±0.6 mg g^{-1} in RA, respectively. The average C/N ratio was 9.6±1.4 in PA and 11.1±0.9 in RA.

4. Discussion

Characteristics of phytopigments and organic matter on surface sediment in Lake Saroma

The average Chl *a* and phaeopigment biomass in Lake Saroma were 299±220 mg m^{-2} and 325±259 mg m^{-2}, respectively. In contrast, in the Gulf of Fos in France where mussels were cultured, the average Chl *a* and phaeopigment biomass were 30±5 mg m^{-2} and 215±58 mg m^{-2}, respectively (PLANTE-CUNY *et al.*, 1993). In the Tasman Bay in New Zealand where mussels were cultured, the average Chl *a* and phaeopigment biomass were 24±18 mg m^{-2} and 67±15 mg m^{-2}, respectively (CHRISTENSEN *et al.,* 2003). However, the average Chl *a* and phaeopigment biomass were 330 mg m^{-2} and 220 mg m^{-2}, respectively, at Skagerrak in Sweden (which is located in the subarctic region) where mussels were cultured (SUNDBÄCK *et al.*, 1996). In Hichirripu lagoon, which is located in the same prefecture as Lake Saroma and where oyster and clam were cultured, the Chl *a* biomass was 226 mg m^{-2} (KAJIHARA *et al.*, 2010). We suggested that the Chl *a* and phaeopigment contents tend to be higher in the subarctic region. The Chl *a*/total ratio in this study indicated that the Chl *a* activity was low, i.e., 0.4, in RA [Fig. 2 (c)], which was greater than the levels of 0.01–0.3 detected in Tasman Bay (CHRISTENSEN *et al.*, 2003). In contrast, the Chl *a*/total ratio was high, i.e., 0.8 in PA [Fig. 2 (c)], which were similar to the levels of 0.7–0.8 at Skagerrak at a depth of 0.5 m (SUNDBÄCK *et al.*, 1996). Therefore, the average relative light intensity at depth of 7 m and 13 m, which were average depth at PA and RA, were 25±17% and 9±6% as 100% in surface layer, respectively in the summer of 2010 (in preparation). The Chl *a* content were high despite the low pheaopigment, TOC, and TN at PA. Thus, at PA, organic matter was low due to sandy and light, which was enough to grow microphytobenthos reached to surface sediments. The contributions rate of Chl *a* to TOC were calculated with C/Chl *a* as 50 (ANTIA *et al.,* 1963) and was 36±28% at PA as against was 17±15% at RA in surface sediments. We suggested that microphytobenthos play a role on bioproduction environment at PA. TERASAKI *et al.* (in preparation) reported that deeper station had characterized by easy to be deposited OM derived from detritus and contribution rate of biodeposition was 50% on surface sediments under the scallop culture facility.

At the Marano and Grado lagoons, connected to the Adriatic Sea, and the Firth of Thames, New Zealand, where mussels were cultured, the TOC content varied from 5 to 15 mg g^{-1} (VITTOR *et al.*, 2012) and from 16 to 19 mg g^{-1} (GILES and PILDITCH, 2006), respectively. At Prince Edward Island, Canada, and Thau lagoon, France, where mussels were cultured, the TOC content varied from 12 to 43 mg g^{-1} (WALKER and GRANT, 2009) and from 42 to 68 mg g^{-1} (ANSCHUTZ *et al.*, 2007), respectively. MAGNI *et al.*, (2009) detected very high TOC levels in two Mediterranean lagoons (the Orbetello and the Venice lagoons) where bivalves were cultured, with values up to 60 and 100 mg g^{-1}, respectively. TOC and TN contents of the surface sediments from Lake Saroma where scallops were cultured is similar to or lower than those observed in coastal areas or lagoons where bivalves were cultured. Therefore, it can be deduced that Lake Saroma does not have an extreme organic load, which was also reported by SONODA *et al.* (2002). The sediments are becoming increasingly eutrophic in RA as reported by KATSUKI *et al.* (2009). The C/N ratio of phytoplankton and microphytobenthos were 4–10, whereas the C/N ratio of seagrass and terrestrial plant was greater than 12 (BORDOVSKI, 1965; HEDGES *et al.*, 1986; MEYERS, 1997). This suggests that TOC and TN are derived from phytoplankton and microphytobenthos in PA, while they are derived from seagrass and terrestrial plant in RA. SAMPEY *et al.* (1997) reported that organic matter mainly derived from phytoplankton was found in center of this lake and organic matter derived from terrestrial material increased near the edge of lake, which was not consistent with this current study. However, the reported organic matter by stable carbon and nitrogen isotopes showed that the contributions of seagrass and terrestrial plant were high in RA, which was consistent with the study by TERASAKI *et al.* (in preparation).

Variation of TOC content of the surface sediments over the past 40 years in Lake Saroma

Aquaculture activities are generally viewed as having major negative impacts on coastal environments (DANOVARO, 2003). The impact of intensive fish farming on the benthic environment is expected to be higher than that of bivalve farming (MAZZOLA *et al.*, 1999; INGLIS *et al.*, 2000). However, mussel biodeposition in mussel farms located in the Mediterranean has adversely affected farm sediments (DANOVARO *et al.*, 2004). In Lake Saroma, previous investigations suggested that high amounts of organic matter were loaded into the sediment by scallop culture (SONODA 2002; KATSUKI *et al.*, 2009). Thus, the TOC content since 1965 during the period of scallop culture (Table 1) was evaluated and related to human activities in the surface sediment. The scallop production was 200 tons in 1965 and increased to 9,000 tons in 1980 (NISHIHAMA and HOSHIKAWA, 1992). In 1965, the spatial distribution of the TOC content was high at around 10–20 mg g^{-1} and greater than 25 mg g^{-1} at both depth > 10 m in east basin and depth > 15 m in west basin (deeper station), where every hypoxia occurred (Table 1). This showed that the benthic environment was highly eutrophic in 1965 and was comparable to 2005, which has a similar level. It was prompted the digging of secondary channel to improve water flow because repeated hypoxia events occurred in 1978. However, fishermen also halted scallop culture, because scallop catches were damaged by a red tide event in the 1980s. Thus, the spatial distribution of the

Table 1. Change of the spatial distribution of total organic carbon (TOC) content in surface sediments over past 40 years. Unit: % (percentage of total area); ton/year (scallop catches).

	total area				scallop catches	digging channel
unit	%				ton/year	
year	rank1	rank2	rank3	rank4		
1929	–	–	–	–	–	the main channel
1965	14	52	16	18	200	
1978	–	–	–	–	7000	the secondary channel
1988	39	56	3	2	5000	
1995	36	27	20	16	6700	
2005	33	19	15	33	6000	

*The rank 1 indicated that TOC content was <10 mg g^{-1}; the rank 2 indicated that TOC content was 10–20 mg g^{-1}; the rank 3 indicated that TOC content was 20–25 mg g^{-1}; the rank 4 indicated that TOC content was >25 mg g^{-1}. The percentages of total area of 1965 and 1988 were taken from NISHIHAMA and HOSHIKAWA (1992); the percentages of total area of 1995 were taken from SAMPEI *et al.* (1997). Cultured scallop catches were running mean values for five years, provided that the scallop catch of 1965 used data of 1966.

TOC content decreased between 10 and 20 mg g^{-1} at deep stations in 1988 and it decreased as compared to that in 1965 (Table 1). The benthic environments were improved by the reduction of scallop biodeposition in the sediment and water flowing through the secondary channel (NISHIHAMA and HOSHIKAWA, 1992). After the fishermen resumed scallop culture at the end of the 1980s, the scallop catches rebounded to 7,000 tons in 1990 (NISHIHAMA and HOSHIKAWA, 1992) and it remained between 6,000 and 7,000 tons in 2005 (AQUACULTURE FISHERY COOPERATIVE OF SAROMA LAKE, 2005). The spatial distribution of the TOC content increased at around 10–20 mg g^{-1}, and the average TOC content was 24 ± 2 mg g^{-1} at deep stations in 1995 (Table 1). After that, the spatial distribution of the TOC content increased to greater than 25 mg g^{-1}, and the average TOC content was 27 ± 2 mg g^{-1} at deep stations in 2005 (Table 1). According to the distributions of the TOC content in 1988 (NISHIHAMA and HOSHIKAWA, 1992), 1995 (SAMPEI *et al.*, 1997), and this current study, the TOC content decreased in PA and increased in RA. The TOC accumulated in the deep stations, and its extent expanded in RA. The TOC content has increased to at least 7 mg g^{-1} at deep stations since 1988, when scallop culture was healthy (Table 1). This suggests that the benthic environments are directly or indirectly affected by human activities such as scallop culture in Lake Saroma, particularly in RA.

Biodeposition was also responsible for a significant accumulation of biopolymeric carbon, which induced significant changes in microbial and meiofaunal assemblages (MIRTO *et al.*, 2000). In Lake Saroma, the polychaete community changed between 1975 and 1995. The total population density and species diversity has decreased, and the dominant species composition has changed (SONODA, 2002). The relative abundance of *Cyclotella caspia*, an indicator species of eutrophication, was higher in 2005 as compared to 1995; it increased in the scallop culture area since 2005 (KATSUKI *et al.*, 2009).

The biogeochemical environment is seriously affected by human activities in Lake Saroma due to the interaction among the TOC content, the scallop culture, and the digging. Furthermore, previous reports state that hypoxic events and eutrophication in benthic environments have been degraded yearly by long-term scallops grazing, which has led to benthic community changes (SONODA, 2002; KATSUKI *et al.*, 2009). It is predicted that if benthic environments are left undisturbed, and if the TOC content continues to increase in the future, this would affect the scallop culture. Nishihama *et al.* (1992) reported that benthic environment was favorable in 1988 and TOC content was < 20 mg g^{-1} at depth > 15 m on surface sediments. In contrast, TOC content was at least 24 ± 1 mg g^{-1} of 1995 while hypoxic events had occurred. Thus, we suggested that TOC content should be < 20 mg g^{-1} to keep favorable benthic environment. In the future, it is important to focus on the TOC content and show voluntary restraint during scallop culture and be proactive in digging the secondary channels to improve benthic environments.

5. Conclusion

Lake Saroma does not have extreme organic contamination, although the sediments are becoming increasingly eutrophic in the organic rich area owing to the concentration of scallop culture facilities. TOC content has continued to increase, and hypoxic events have occurred at deep stations that are in the RA since the early 1990s. The TOC content respond to human activities such as scallop culture and digging in Lake Saroma. We suggested that effective action needed to be taken to improve benthic environments as soon as possible because the average TOC content is 27 mg g^{-1} at deep stations in 2005.

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