

METABOLIC CIRCULATION OF PHOSPHORUS AND NITROGEN IN MATSUSHIMA BAY (JAPAN) WITH SPECIAL REFERENCE TO EXCHANGE OF THESE ELEMENTS BETWEEN SEA WATER AND SEDIMENTS *

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CONTENTS

| | |
|--|----|
| I. INTRODUCTION | 11 |
| II. GENERAL DESCRIPTION OF MATSUSHIMA BAY | 13 |
| III. GENERAL CHARACTERS OF SEA WATER IN THE BAY | 15 |
| A. Current in the Bay | |
| B. Outline of the Regional Distribution of Nutrient Elements | |
| C. Seasonal Variation in Several Elements of Sea Water | |
| D. Chemical Character of the River Water Flowing into the Bay | |
| IV. PHYSICAL AND CHEMICAL PROPERTIES OF SEDIMENTS | 23 |
| A. Physical Properties | |
| B. Chemical Properties | |
| C. Discussion on the Values of N/P and C/N | |
| D. Soluble Nutrients in Sediments | |
| V. PRIMARY PRODUCTION AND STANDING CROP OF NET PLANKTON IN SHIOGAMA HARBOR | 55 |

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| | |
|---|-----|
| A. Method Employd for Estimation of Primary Production | |
| B. Results of Primary Production | |
| C. Relation between Compensation Point and Transparency | |
| D. Productive Efficiency of Phytoplankton for the Solar Radiation Energy | |
| E. Standing Crop of Net Plankton | |
| VII. MATERIALS SUSPENDED IN THE BAY | 69 |
| A. Method of Collecting Materials Suspended | |
| B. Vertical Distribution of Materials Suspended and their Biological and Chemical Composition | |
| C. Seasonal Variation of Materials Suspended and their Biological and Chemical Composition | |
| VIII. METABOLISM OF NUTRITIVE ELEMENTS IN SEDIMENTS | 78 |
| A. Decomposition of Organic Matter in Sediments and Liberation of Soluble Nutrients | |
| B. Return of Soluble Nutrients from Sediments into Overlying Sea Water | |
| C. Transformation of Inorganic Nitrogen on the Surface of Sediments | |
| IX. AN ATTEMPT AT QUANTITATIVE ESTIMATION OF NITROGEN VARIATION AT THE BOTTOM SURFACE | 96 |
| A. Theoretical Study on Quantitative Estimation of Nitrogen Variation at the Bottom Surface | |
| B. An Annual Variation of Nitrogen at the Bottom Surface in Shiogama Harbor | |
| C. An Annual Balance of Nitrogen at the Bottom Surface | |
| X. A CYCLE OF NUTRIENT SUBSTANCES IN ZOSTERA AREA | 112 |
| A. Life-Cycle of Eel-Grass, <i>Zostera marina</i> | |
| B. Seasonal Variation of Nitrogen and Phosphorus Contents in <i>Zostera marina</i> | |
| C. Chemical Characteristics of Sea Water and Sediments in <i>Zostera</i> Area | |
| D. Quantitative Relation between the Contents of Nitrogen and Phosphorus in <i>Zostera marina</i> and those in Sediments during Life-Cycle of <i>Zostera marina</i> | |
| XI. AN OUTLINE OF BIOLOGICAL PRODUCTION IN MATSUSHIMA BAY | 137 |

| | |
|---|-----|
| A. Solar Radiation Energy | |
| B. Approximate Values of Production of Various Plants | |
| C. Standing Crop of Plankton | |
| D. Standing Crop and Net Production in Animals | |
| E. Existing Amount of Easily Decomposable Nitrogen in Sediments | |
| F. Discussion | |
| XI. GENERAL CONCLUSIONS | 144 |
| XII. ACKNOWLEDGEMENTS | 146 |
| XIII. REFERENCES | 149 |

I INTRODUCTION

The principal process of metabolic circulation of material in water is the organic production and the decomposition of organic matter. Although this former includes various stages, namely, from the primary production to the commercial production, the primary production of them is of importance because it is the basis of the ultimate food cycle in the sea. Estimates of the primary production have been made by many workers by various methods. They have been made from the amount of chlorophyll by Manning and Juday (1941), Hogeau et al (1952), from the seasonal fluctuation of the concentration of phosphorus in the sea water by Atkins et al (1954), Harvey (1950), Steele (1956), from the relation between the oxygen difference and the concentration of phosphorus by Matsudaira and Iwasaki (1956). Furthermore, Riley's "light-and-dark bottle oxygen method" and Steemann Nielsen's C^{14} method should be included in the most significant studies.

Estimates of the decomposition of organic material in sea water have been made by many workers. von Brand, Rakestraw and Renn (1937, 1939) have shown interesting results on the regeneration of nitrate from marine plankton during its decomposition. Cooper (1937) has considered the various modes of possible transformation of nitrogen in its decomposition process as they affected the nitrogen cycle in the sea. Cooper (1935) has reported that the liberation of phosphate-P appeared more rapidly in the zooplankton samples than in the diatom material during storage. Waksman et al (1933) showed a relation between the chemical composition of marine algae and their decomposition rate. Seiwel et al (1938) and Okubo (1954, 1956) described the decomposition of sinking remains of plankton organisms and its relation to nutrient liberation. In metabolic circulation of matter in the sea, the rôle of the organic material in marine sediments has been called attention to by many workers. Waksman and his group, and Trask have studied systematically the marine humus from this point of view. The oxygen consumption of sediments as an indication of effective organic matter content was examined by Waksman (1938), and Anderson (1939). From the view point of its effect on the environment of biological condition, the same estimate was made by Motoda

(1939), Kawamura (1940), Kato and Matsudaira (1940). Kato (1949) Kurashige and Ota (1942) and Okuda and Kato (1952) investigated the factors controlling the oxygen consumption of marine sediments. The vertical distribution of phosphorus and nitrogen in sediments was determined by Moor (1930). The examination on the decomposition of organic matter in sediments was made by Waksman, Carey and Reuszer (1933). The distribution of bacteria in sediments was studied by many workers [Reuszer (1933), Lloyd (1931), Waksman, Reuszer, Carey, Hotchkiss and Renn (1933), ZoBell, Anderson (1936) and Kadota (1954)].

Riley (1951) reported that the greater part of phytoplankton produced in the photosynthetic zone may be oxidized to CO_2 in the layer of water less than 200m deep. Because the organic matter produced in photosynthetic zone in the ocean may be decomposed gradually while sinking from the photosynthetic zone to the sea bottom, the only resistant fractions for bacterial action may be reached on the bottom. Since the organic matter produced in the shallow water may reach on the bottom in a shorter time than that in the ocean, the sediments in shallow water may contain a greater fraction of undecomposed organic matter.

Waksman and Hotchkiss (1938) demonstrated that the rate of oxidation of the organic matter from bottom deposits nearer to land and from shallow basins is considerably greater than that from the bottom at greater depths and distances. Furthermore, he has reported that the organic matter in these bottoms is much more resistant to the oxidizability being only one-fifth of that of organic matter in shallower bottoms near shore. Kato (1952) showed that stable humic substances made up from one third to one half of the organic materials in the shallow bay (Utsu Bay in Japan).

Accordingly, it may be concluded that although the rôle of the ocean sediments in the metabolic circulation of organic matter is not important from the quantitative stand point, the sediments in shallow water may play an important rôle qualitatively as well as quantitatively. Without distinction between ocean or shallow water, there are many important ecological and geochemical problems involved in the exchange process of various substances between the sediments and the overlying sea water at the bottom.

The organic matter which reaches on the bottom, in shallow water, may be decomposed by bacterial and chemical action, and although most of it may be soon brought again into the overlying sea water, a part of it may be eaten by the benthonic animals and the remainder will stay on the bottom.

However, our knowledge of the metabolic circulation on the sea bottom is still very limited, and with a few exceptions the available information is largely based upon speculation rather upon experimental evidence.

The present study was designed to elucidate information on the

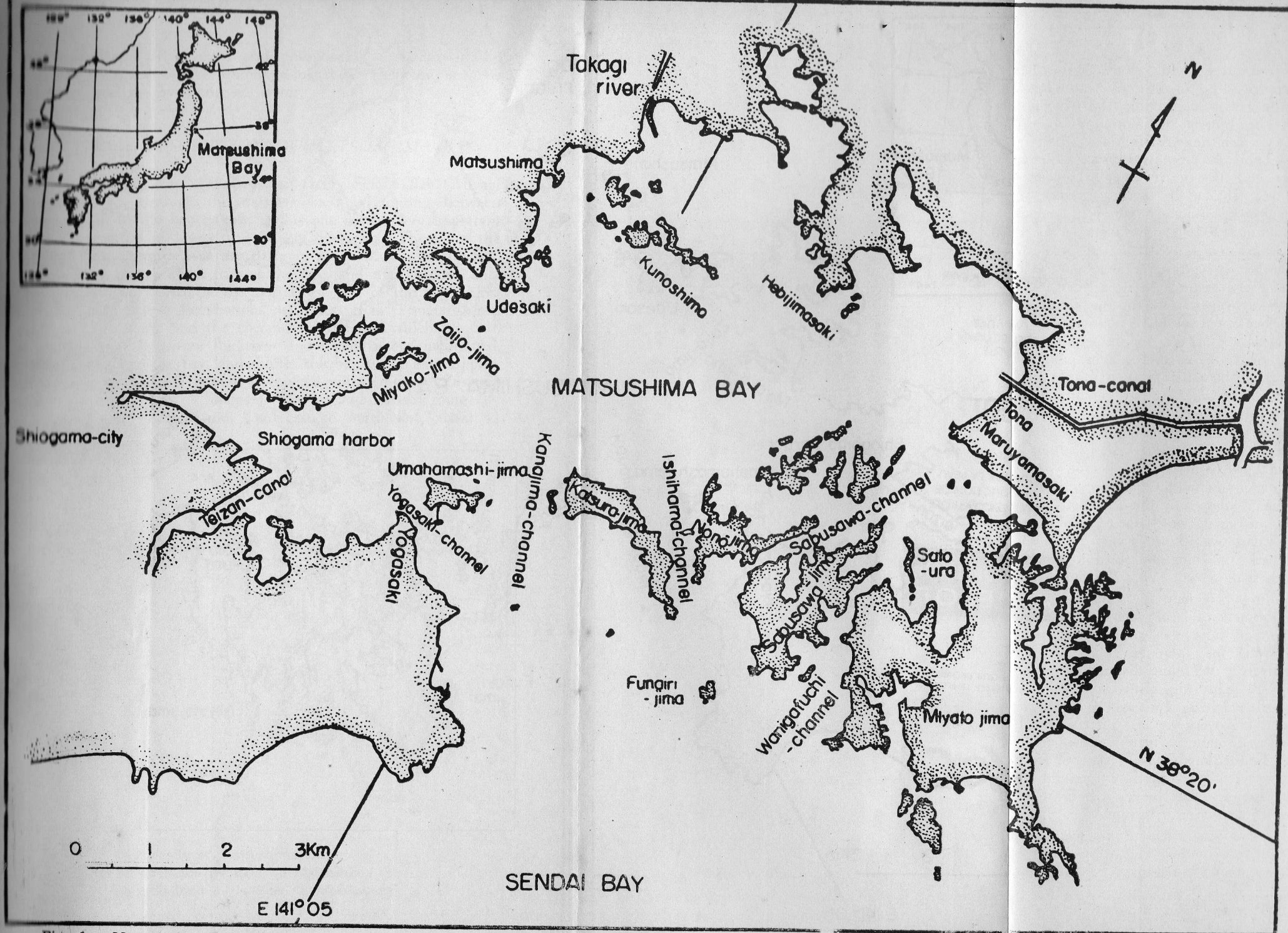


Fig. 1 — Map of Matsushima Bay
 Mapa da Baía de Matsushima
 Carte de la Baie de Matsushima

metabolic circulation of nitrogen and phosphorus in shallow water, with special reference to the exchange of these elements between the sediments and the overlying sea water.

II. GENERAL DESCRIPTION OF MATSUSHIMA BAY

Matsushima Bay (Fig. 1), opens out facing Sendai Bay (Miyagi Prefecture, Japan), through the narrow channels running between the many islands in the bay mouth, and is one of the very important fields for the culture of lavers and oysters in Japan. There are the Tona Canal connecting the Naruse River in the north-east of the bay, the Takagi-River in the north part of the bay, and the Teizan Canal in Shiogama Harbor located in the north-west part of the bay. Most areas of the bay have a flat bottom, with less than 3 meters deep except for the sea route and the entrance of the bay which are 5-10 meters deep (Fig. 2). From the river and canals above mentioned, fresh water flows into the bay, and dilutes the bay water and supplies nutrients. Most of the bay bottom is covered with eel-grass (*Zostera*) except for the inner parts of Shiogama Harbor and the sea route.

The long axis extends from south-east to north-west, about 11

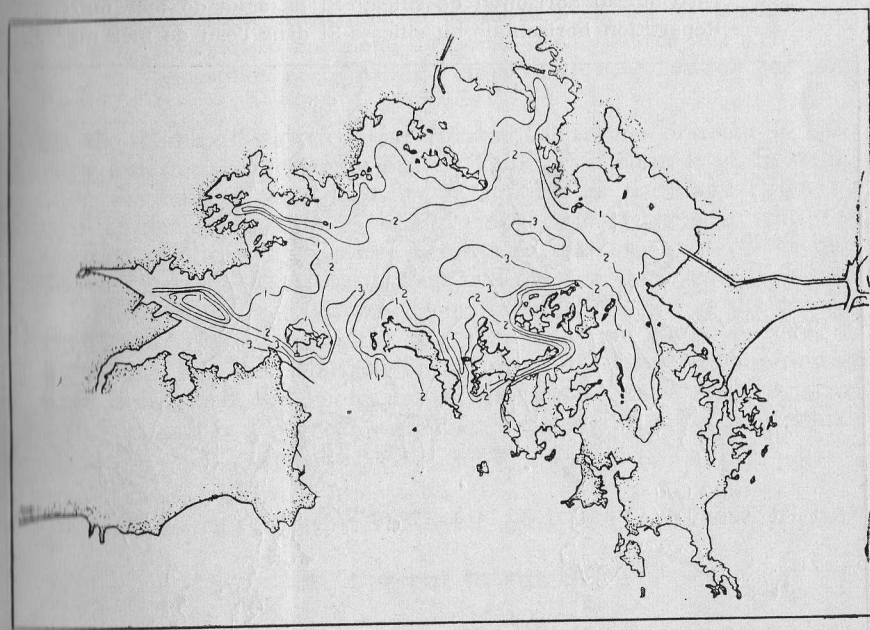


Fig. 2 — Bottom topography of Matsushima Bay
Topografia do fundo da Baía de Matsushima
Topographie du fond de la Baie de Matsushima

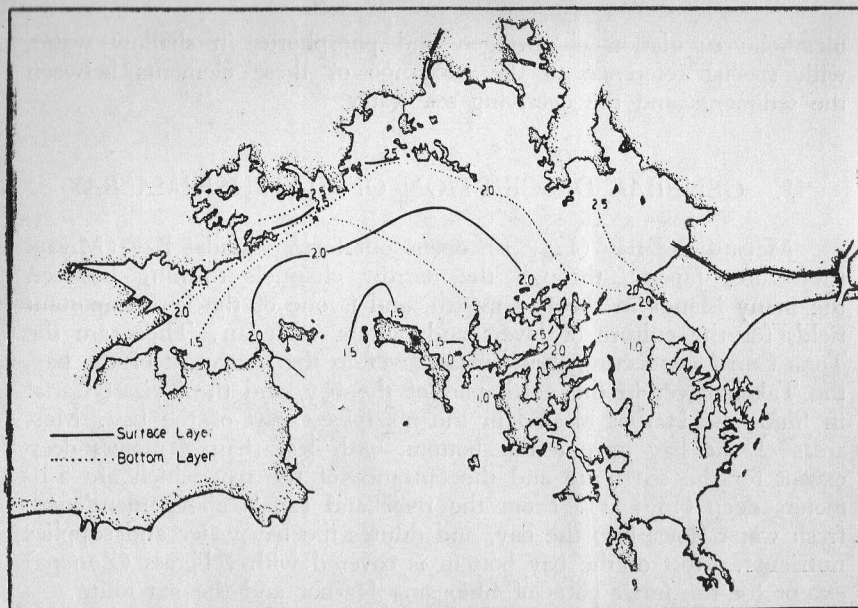


Fig. 3 — Horizontal distribution of silicate-Si in sea water mg/L
Distribuição horizontal de silicato-Si na água do mar mg/L
Répartition horizontale du silicate-Si dans l'eau de mer mg/L

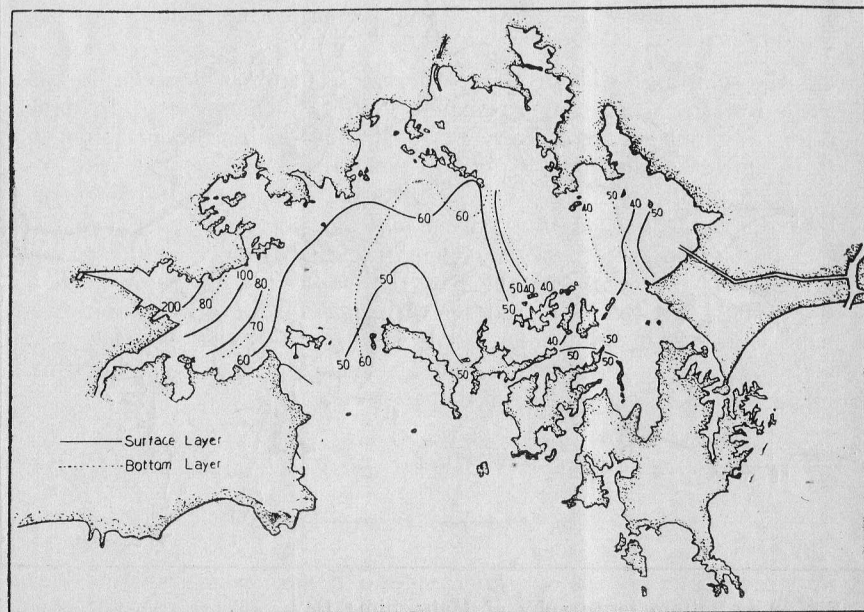


Fig. 4 — Horizontal distribution of ammonia-N in sea water γ/L
Distribuição horizontal de amônia-N na água do mar γ/L
Répartition horizontale del 'ammoniac-N dans l'eau de mer γ/L

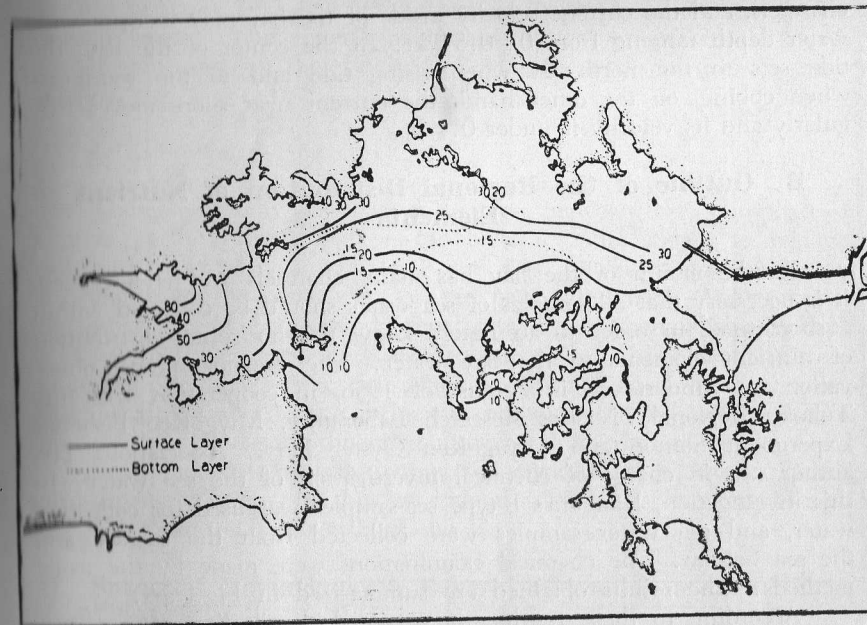


Fig. 5 — Horizontal distribution of phosphate-P in sea water γ/L
Distribuição horizontal de fosfato-P na água do mar γ/L
Répartition horizontale du phosphate-P dans l'eau de mer γ/L

km, the short axis is about 5 km. The bay has an area of about 40 km², and a water capacity of approximately 9×10^3 m³ at mean level. In spring tides, the half of water capacity in the bay is risen and fallen by tidal currents, although its quality may be not changed with the variation of the water capacity because of the some part of the out-flowed water will be returned again into the bay in the next high tide.

Furthermore, the following point should be added as the oceanographical characteristics in the bay, that is, as the bay is in shallow, the waters may be subjected an influence of the strong north-west wind during fall and winter, consequently, the water may be mixed vertically, and a good deal of bottom sediments may be often stirred up and may be suspended in the water.

III. GENERAL CHARACTERS OF SEA WATER IN THE BAY

A. Current in the Bay

According to the observation of 2nd Regional Marine Safety Head Quarters Hydrographic Division, the current in the bay may be described as follows: The velocity of the current in the Kanazima Channel and the Ishihama Channel is from 0.5-1.25 kt faster than that in other

channels, and the current velocity inside of the bay may increase with water depth ranging from 0.1-0.55 kt. In the center of the bay, the tide sets to the north-east when rising tide and to the south-east when ebbing, on the other hand, the current near shore moves irregularly and its velocity is under 0.1 kt.

B. Outline of the Regional Distribution of Nutrient Elements

As the mouth of the bay has many channels and is not deep, it is necessary that all samples of sea water should be collected within a short time, in order to accurately know the horizontal distribution of nutrient elements in the bay water. The oceanographical observation was undertaken in August of 1956, in cooperation with the Tohoku Regional Fisheries Research Laboratory, Miyagi-Ken Fisheries Experiment Station and Miyagi-Ken Oyster Larvæ Association. The author was in charge of chemical investigation of the sea water. In this investigation, Kitahara's B-type sea-sampler was used for collecting water, and sea water samples were collected from the surface and the sea bottom. The chemical examinations were made by the usual methods. The results obtained are summarized in Fig. 3-5.

According to these results, the regional distribution of nutrients may be stated briefly as follows.

1. Silicate-Si

In general, the silicate-Si content in the surface water (1.2-2.7 mg/L) was higher than that at the bottom (0.77-2.6 mg/L). There was a tendency for it to increase from the entrance of the bay to the inner part. The highest concentration of silicate-Si was found in the water of the inner part which is affected more by the fresh water from the Tona Canal and the Takagi River.

2. Ammonia-N

There was never very much difference between the ammonia-N at the surface and that on the bottom, except in the inner part of Shiogama Harbor. The greatest abundance in ammonia-N was found in the inner part of Shiogama Harbor, and a relatively small amount in the north-east region of the bay.

3. Nitrite-N, Nitrate-N

These data are not shown in the tables or figures. The presence of nitrite-N could not be detected in many regions, with a few exceptions in the inner part of Shiogama Harbor (1-3 γ /L).

On the other hand, the nitrate-N content varied rather irre-

gularly between 1-90 γ /L in the surface water and 3-48 γ /L in the bottom water. The amount of nitrate-N was greater in the north-east region and in the vicinity of Hamada, compared with other regions.

4. Phosphate-P

There was only a small difference between the phosphate-P content at the surface and on the bottom. With regard to regional distribution of the phosphate-P, it was found to increase from the mouth to the inner part of the bay. Phosphate-P contents in the inner part of Shiogama Harbor were higher than in the others.

As this investigation was carried out at beginning of the decomposition stage of *Zostera*, the regional distribution of these nutrients may be attributable to the influences not only of fresh water flowing into the bay but also of liberated nutrients from *Zostera*.

From the above results, it may be concluded that the distribution of nutrient elements in the bay shows a tendency to decrease from the inner part to the mouth of the bay.

C. Seasonal Variations in Several Elements of Sea Water

As to the seasonal variations of various elements of sea water, the author reported earlier the monthly results from December, 1952 to February, 1955. In the present report, this problem will be further discussed together with new data based on subsequent observations. (March 1955 to May 1956).

The sea water samples were collected from the same stations as those reported in the earlier paper (Fig. 6). Most collections of sea water were made once a month at the neap tides. In the investigations, Kitahara's B-type sea sampler and Tamura's syphon sea-sampler (1942) were used, the latter especially for collecting water from near the bottom. At the time of collection, a mixed solution of toluen and chloroform (1:1) was added to the sea water to stop bacterial action. The chemical examinations were made by the usual methods. The results obtained are shown in Fig. 7 and 8.

1. Temperature of sea water

The highest water temperatures usually occurred in August or September, and the lowest in January or February. The regional difference of water temperature was great in summer and winter, and was about 2 or 3°C. The annual difference of water temperature was about 25°C. The water temperature shows a tendency to decrease from the inner part of the bay to the bay mouth in summer, while in winter this tendency is reversed.

The water temperature may be influenced by air temperature

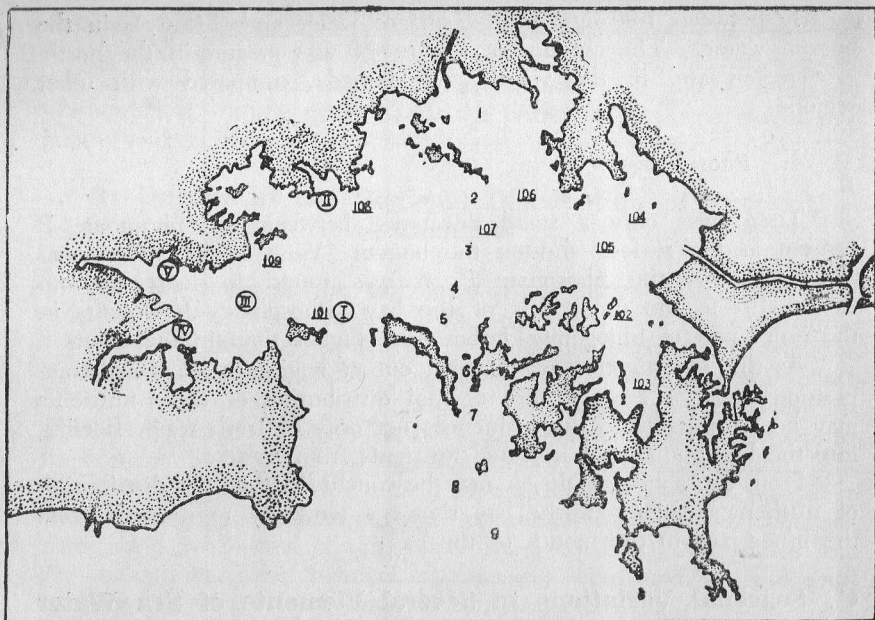


Fig. 6 — Stations observed in Matsushima Bay
 Estações observadas na Baía de Matsushima
 Stations observées dans la Baie de Matsushima

I — V.....

Stations observed on seasonal variation of physical and chemical properties of sea water and of sediments

Estações observadas na variação estacional das propriedades físicas e químicas da água do mar e dos sedimentos

Stations observées pour la variation saisonnière des propriétés physiques et chimiques de l'eau de mer et des sédiments

1 — 9

Stations showed cumulative curves of mechanical analysis in various types of sediments

Estações indicando curvas cumulativas das avaliações mecânicas em vários tipos de sedimentos.

Stations donnant les courbes cumulatives des analyses granulométriques dans différent types de sédiments

101 — 109

Stations estimated the content of nitrogen and of phosphorus in the particle fraction of different size of sediments

Estações estimando o teor de nitrogênio e de fósforo nas partículas fracionadas de diferentes tipos de sedimentos

Stations utilisées pour la teneur en azote et la phosphore dans les las différentes fractions granulométriques des sédiments

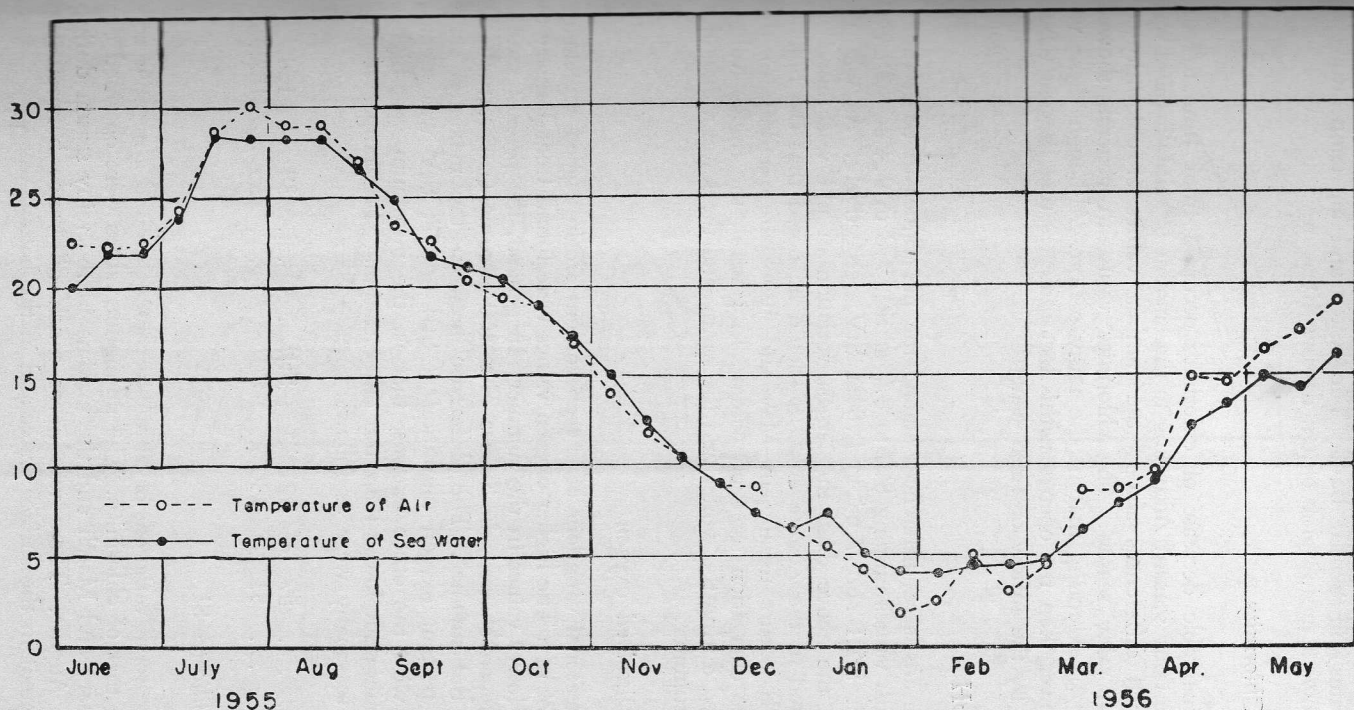


Fig. 7 — Seasonal variation of temperature of water and of air
 Variação estacional da temperatura da água e do ar
 Variation saisonnière de la température de l'eau et de l'air

and also by the Oyashio Current (cold water) and the Kuroshio Current (warm water) in Sendai Bay.. The water and air temperature in Fig. 7 shows a mean value of ten days at 10 a. m.

2. Chlorinity

A remarkable decrease of chlorinity occurred from June to August in the rainy season. According to the amount of rainfall, there was found much differences among the minima values of chlorinity in the annual rainy season. The chlorinity value, in general, showed 17 to 18‰ excepting that in the rainy season. Although these values are lower than the open sea, this fact indicates that the sea water is diluted by the inflow of fresh water.

3. pH

There are large differences among the pH values in the stations, that is, with values ranging 8.0 to 8.7 at StI, 7.8 to 9.4 at StII, 7.9 to 8.95 at StIII and 7.65 to 8.8 at StV, respectively. As will be seen from the above data, the largest variation in pH was found in St II located in the *Zostera* area. It should be noted that the highest pH at StII occurs usually in May and June corresponding to the most active elongation stage of *Zostera*. In general, the higher values are obtained during the winter and the spring and the lower values during the summer.

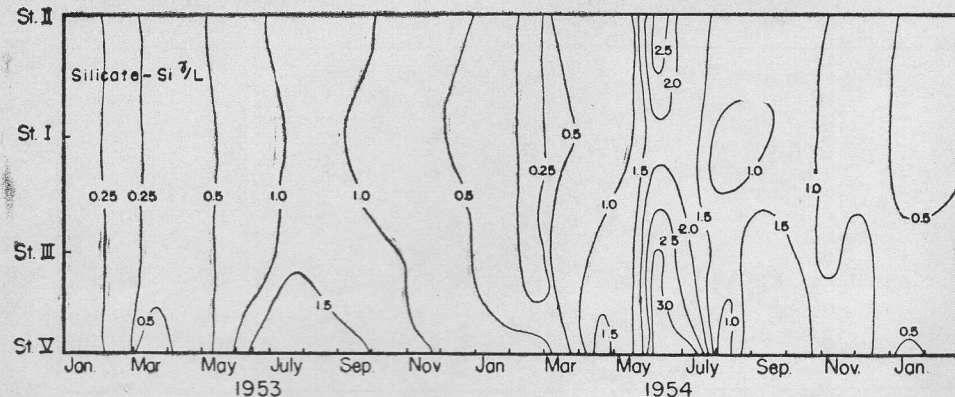
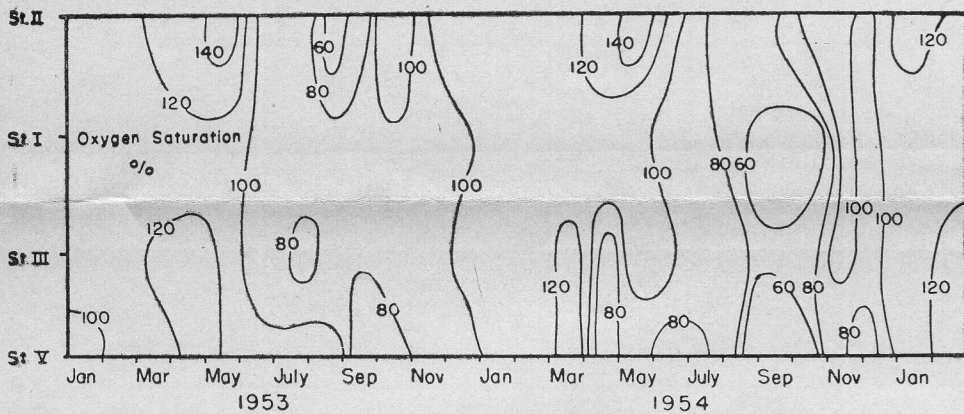
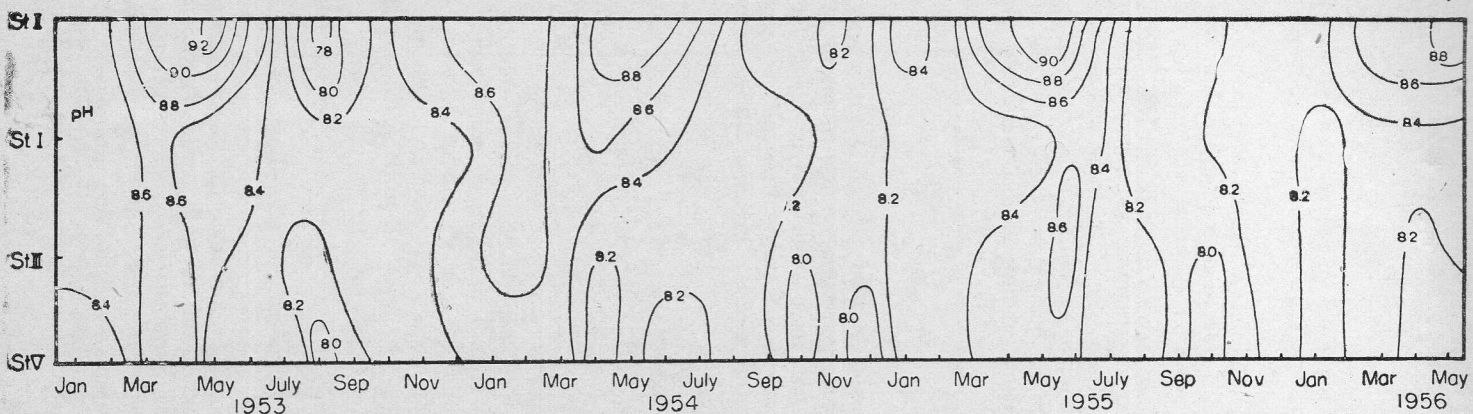
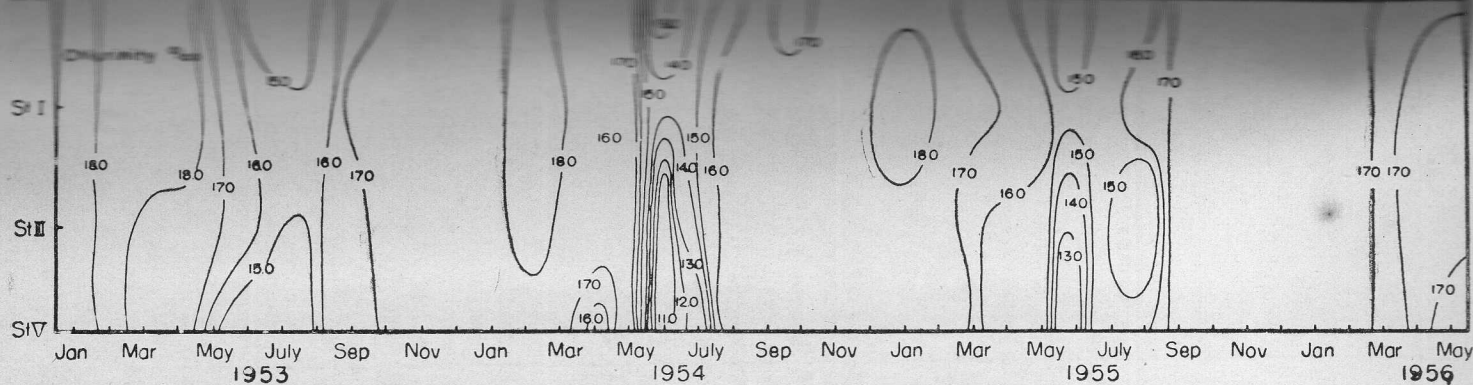
4. Dissolved oxygen

The seasonal variations of oxygen content are in a good agreement with that of pH. The higher oxygen values were found from January to May, the lower values in the summer. In general, the percent saturation of oxygen showed the values over 100 percent (supersaturated) excepting the summer. The difference between the maximum and minimum percent oxygen saturation at StII and at StV was greater compared with the other stations, that is, the maximum was higher and the minimum lower than the other stations. The ranges in the variations seasonally were as follows:

| | | | |
|-----------------|------------|----------------|------------|
| StI | 57 — 121%, | StII | 38 — 158%, |
| StIII | 51 — 130%, | StV | 30 — 182%, |

5. Silicate—Si

The seasonal variations of silicate-Si content showed a negative correlation to that of chlorinity. The minimum values were obtained during February and March and the maxima in the rainy season during June and August. There was never much difference between the silicate content in the surface water and in the bottom water.



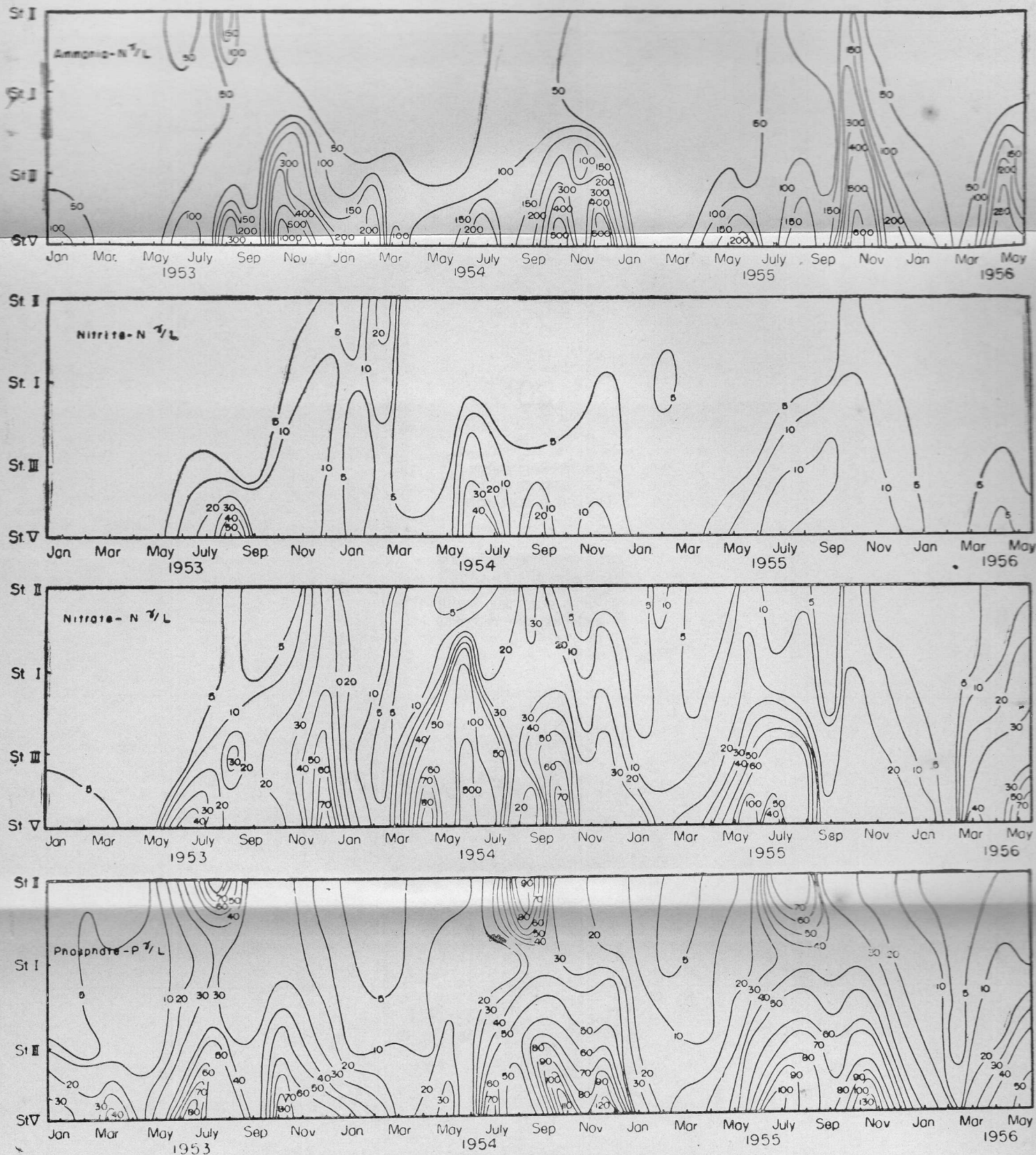


Fig. 8 — Seasonal variation of properties of sea water
 Variação estacional das propriedades da água do mar
 Variation saisonnière des propriétés chimiques de l'eau de mer

6. Ammonia-N

The ammonia-N content may be summarized by stating that the highest content of ammonia-N generally was found at StV, next at StIII and the least at StI and StII.

The range of ammonia-N content was 10-300 γ /L at StI, 10-250 γ /L at StII, 10-450 γ /L at StIII and 20-1,200 γ /L at StV.

The higher values occurred during the summer and the early winter and the lower values in the other seasons.

It should be noted that the highest value of ammonia-N content was not found during the rainy season, contrary to the results with silicate. The amount of ammonia-N may be influenced not only by the inflowing river water, but also by the decomposition of organic matter in the sea water and in the sediments and the polluted water from the city.

7. Nitrite-N

When comparing the upper water with the bottom water, the larger content of nitrite-N was found in the bottom water, although this is not very pronounced. In general, higher values of nitrite-N at StIII and StV were found during the rainy season, but this was not the case at StI and StII. The ranges in the seasonal variations in nitrite-N were as follows:

| | | | |
|-----------------|-------------------|----------------|-------------------|
| StI | 0-25 γ /L. | StII | 0-56 γ /L, |
| StIII | 0-31 γ /L, | StV | 0-84 γ /L, |

8. Nitrate-N

The seasonal variation in nitrate-N was irregular compared with the other nutrients, although higher values were often found in the rainy season. The maximum values of nitrate-N at StIII and StV were much larger than StI and StII, namely, 12 γ /L at StI, 38 γ /L at St II, 800 γ /L at St III and 820 γ /L at St V.

9. Phosphate-P

The seasonal variation in phosphate-P was in reasonably good agreement with ammonia-N.

The high values of phosphate-P at StII were found during a short period from July to September corresponding to the decomposition stage of *Zostera*, while at other stations they occurred during summer and early winter. When comparing the values of phosphate-P between stations, the highest value generally was found at StV, and the lowest value at StI. The ranges of the seasonal variations in phosphate-P were as follows:

| | | | |
|-----------------|-------------------|----------------|--------------------|
| StI | 2-48 γ /L, | StII | 0-105 γ /L, |
| StIII | 2-98 γ /L, | StV | 4-160 γ /L. |

As a great proportion of the water of Mastushima Bay may be changed by the tides, the physical and chemical properties of bay water are influenced by the two different water masses of the Oyashio Current (cold water) and the Kuroshio Current (warm water). On the other hand, the industrial sewage water and the flowing river water may also influence the bay water properties.

In general, the seasonal variations in dissolved oxygen and pH values are in inverse proportion to the nutrients (ammonia-N and phosphate-P). The cause of such seasonal variations may be attributable to the production and decomposition of organic matter in the area. The production of organic matter through photosynthesis of plants leads to the increase of dissolved O_2 and of pH value in accordance with the intake of the carbonate and the liberation of O_2 by plants. On the contrary, the decomposition of organic matter causes a decrease of dissolved O_2 and of pH value as a result of the liberation of carbonate and the consumption of oxygen. On the other hand, the soluble nutrients in sea water increase by the decomposition of organic matter and decrease through the photosynthesis of plants.

The seasonal variations of several elements at StII show a difference from the other areas. This may be attributable to a special effect of *Zostera* and will be discussed in a later chapter.

D. Chemical Character of the River Water Flowing into the Bay.

As mentioned previously, chlorinity in Matsushima Bay is lower than 18‰ generally, on account of dilution by the fresh water from the rivers. In order to learn the influences of the fresh water on the nutrient content of bay water, the nutrient content of river was determined at the river mouth at neap tide.

The local distribution of these rivers is shown in Fig. 1 and the geographical conditions of these rivers are as follows;

| | Width of river (m) | Water depth (m) |
|--------------|--------------------|-----------------|
| Takagi-River | 40 — 60 | 1 — 2 |
| Tōna-Canal | 20 | 2 |
| Teizan-Canal | 20 | 2 |

The results obtained are shown in Table 1, and the order of the concentrations of each element among these rivers are summerized as follows;

TABLE 1
Seasonal variation of chemical properties of river water
Variação estacional das propriedades químicas da água do rio
Variation saisonnière des propriétés chimiques de l'eau du fleuve

TONA CANAL

| Date | Layer | Water temp.°C | pH | Cl ‰ | Si mg/L | P _γ /L | NO ₂ -N _γ /L | NO ₃ -N _γ /L | NH ₃ -N _γ /L |
|---------------|---------|---------------|---------|-------|---------|-------------------|------------------------------------|------------------------------------|------------------------------------|
| Dec. 16, 1956 | Surface | 2.1 | 8.0 | 6.01 | 11 | 17 | 1.5 | 70 | 70 |
| Apr. 10, 1957 | " | 10.4 | 8.4-8.5 | 12.72 | 5 | 11 | 3.5 | 90 | 50 |
| " | Bottom | 10.6 | 8.5 | 12.57 | 4.8 | 21 | 1 | 70 | 80 |
| May 17, " | Surface | 19.8 | 8.6 | 10.49 | 4.5 | 23 | 0 | 60 | 40 |
| June 29, " | " | 22.0 | 8.5 | 8.31 | 5.5 | 27 | 2.5 | 70 | 250 |
| Aug. 10, " | " | 24.2 | 7.0 | 1.63 | 10 | 3 | 3 | 15 | 150 |
| Oct. 21, " | " | 14.0 | 8.0 | 7.51 | 9.6 | 28 | tr | 7 | 60 |

TAKAGI RIVER

| Date | Layer | Water temp.°C | pH | Cl ‰ | Si mg/L | P _γ /L | NO ₂ -N _γ /L | NO ₃ -N _γ /L | NH ₃ -N _γ /L |
|---------------|---------|---------------|-----|------|---------|-------------------|------------------------------------|------------------------------------|------------------------------------|
| Dec. 16, 1956 | Surface | 1.4 | 7.3 | 2.47 | 15 | 30 | 2.5 | 140 | 230 |
| Apr. 16, 1957 | " | 12.5 | 8.2 | 4.41 | 11 | 24 | 6 | 200 | 500 |
| " | Bottom | 12.5 | 8.2 | 4.33 | 11 | 26 | 5.5 | 200 | 440 |
| May 17, " | Surface | 19.5 | 7.3 | 1.48 | 11 | 12 | 14 | 190 | 100 |
| May 29, " | " | 19.8 | 6.8 | 0.34 | 8.5 | 20 | 32 | 200 | 400 |
| May 29, " | Bottom | 20.1 | 6.7 | 0.37 | 9.2 | 25 | 28 | 350 | 400 |
| June 29, " | Surface | 20.4 | 6.9 | 0.31 | 7.4 | 24 | 2 | 20 | 200 |
| Aug. 10, " | " | 24.4 | 6.7 | 0.10 | 12 | 10 | 7 | 7 | 250 |
| Oct. 21, " | " | 12.9 | 7.4 | 4.51 | 11 | 35 | tr | 9 | 100 |

TEIZAN CANAL

| Date | Layer | Water temp.°C | pH | Cl ‰ | Si mg/L | P _γ /L | NO ₂ -N _γ /L | NO ₃ -N _γ /L | NH ₃ -N _γ /L |
|---------------|---------|---------------|------|------|---------|-------------------|------------------------------------|------------------------------------|------------------------------------|
| Dec. 16, 1956 | Surface | 1.8 | 7.5 | 7.69 | 10 | 37 | 16 | 200 | 350 |
| Apr. 17, 1957 | " | 13.3 | 7.45 | 7.57 | 8.4 | 60 | 17 | 180 | 700 |
| " | Bottom | 13.6 | 7.3 | 7.59 | 8.4 | 65 | 17 | 180 | 640 |
| May 16, " | Surface | 18.5 | 7.5 | 6.69 | 7.2 | 100 | 18 | 100 | 490 |
| May 29, " | " | 19.2 | 7.7 | 8.11 | 4.7 | 93 | 29 | 150 | 1,100 |
| May 29, " | Bottom | 19.0 | 7.7 | 8.01 | 5 | 56 | 29 | 150 | 1,090 |
| June 30, " | Surface | 22.0 | 7.0 | 2.26 | 7.4 | 32 | 1 | 80 | 150 |
| Aug. 11, " | " | 25.0 | 6.9 | 0.98 | 11 | 100 | 30 | 100 | 700 |
| Oct. 20, " | " | 13.5 | 7.2 | 7.91 | 13 | 200 | tr | tr | 1,590 |

| | | | | | |
|---------------|-----------|---|-----------|---|-----------|
| chlorinity—Cl | Tōna—C. | > | Teizan—C. | > | Takagi—R. |
| silicate—Si | Takagi—R | > | Teizan—C. | > | Tōna—C. |
| pH | Tōna—C. | > | Takagi—R. | > | Teizan—C. |
| nitrate—N | Takagi—R | > | Teizan—C. | > | Tōna—C. |
| nitrite—N | Teizan—C. | > | Takagi—R. | > | Tōna—C. |
| ammonia—N | | | | | |
| phosphate—P | | | | | |

The nutrients content except for nitrite—N in these rivers is generally higher than in the bay water, therefore the fresh water flowing from these rivers into the bay increases the nutrients content of the bay water.

Summary

According to these results, the oceanographical characteristics in the bay water may be stated briefly as follows:

(1) As the water capacity of the bay is very small compared with the bay area because of shallow depth, the water in the bay may be changed considerably by tidal currents.

(2) From the river and the canals, a fairly large amount of fresh water flows into the bay, and serves to dilute the bay water or increases the concentration of nutrients.

(3) There are three different water types affecting on the properties of the water in the bay; (a) the open water flowing through the five channels, (b) fresh river water flowing into the bay which enrich in nutrients, (c) sewage water which has abundant dissolved organic matter and soluble nutrients.

IV. PHYSICAL AND CHEMICAL PROPERTIES OF SEDIMENTS OF MATSUSHIMA BAY

In a previous paper (Okuda and Sato, 1955), the local distribution of several properties of sediments was reported. This paper reports additional observations on the local and vertical distribution of physical and chemical properties.

A. Physical Properties

1 Temperature of sediments

Temperature of sediments is an important factor affecting the activity of benthonic animals and the decomposition of organic matter in sediments.

The vertical distribution of temperature of sediments shows the characteristic change seasonally, although the temperature of sediments varies generally in keeping with the seasonal variation of water temperature as shown in Fig. 9.

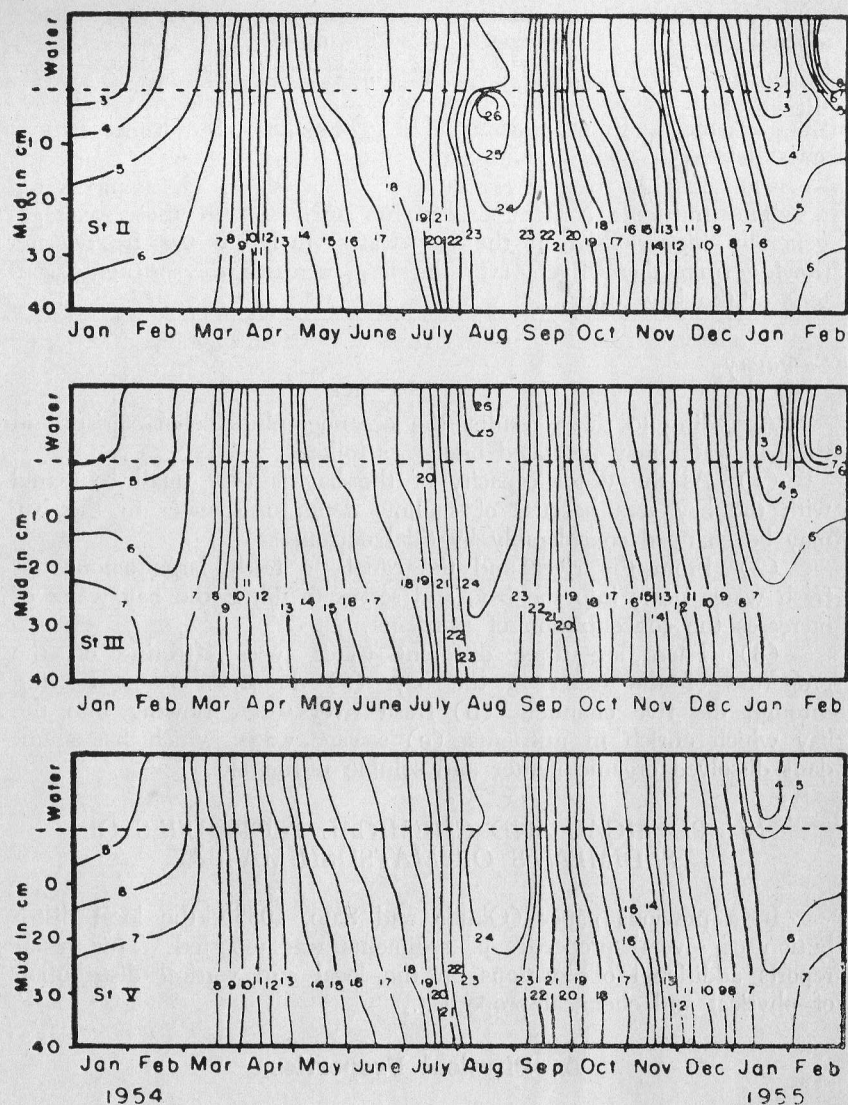


Fig. 9 — Seasonal variation of vertical distribution of temperature of sea water and sediments

Variação estacional da distribuição vertical da temperatura da água do mar e sedimentos

Variation saisonnière repartition verticale de la température de l'eau de mer et des sédiments

In the season of descending air temperature (from October to February), the highest temperature was found in the deepest layer (about 40 cm) of sediments, and the temperature increases generally from surface water to this layer of sediments. In the season of rising air temperature (from March to September), on the other hand, the highest temperature was observed at the water surface, increasing gradually from deepest layer (about 40cm) of sediments to the water surface.

In general, the ranges of the annual variations in temperature decreased gradually with depth from surface water to the deepest sediments layer as follows:

Annual range

| | |
|-------------------|-----------------------------|
| Surface water | 23.8 (StIV) — 28.5 (StII)°C |
| Bottom water | 20.3 (StIV) — 27.8 (StII)°C |
| Surface sediments | 19.7 (StI) — 28.8 (StII)°C |
| Deepest sediments | 16.8 (StIV) — 18.3 (StII)°C |

T A B L E 2

Physical properties of sediments
Propriedades físicas dos sedimentos
Propriétés physiques des sédiments.

| LOCALITY | | Outer area of the bay | Entrance area of the bay | Intermediate area of the bay | Inner area of the bay | Mouth area of the river |
|--------------------------|---------|-----------------------|--------------------------|------------------------------|-----------------------|-------------------------|
| Medium (Md) in diameter | Max. | 2,330 | 300 | 58.0 | 9.8 | 179 |
| | Min. | 162 | 21.0 | 3.1 | 3.1 | 57.0 |
| | Average | 772 | 85.0 | 18.5 | 5.4 | 124 |
| > 10μ, in diameter % | Max. | tr | 42.5 | 76.6 | 73.2 | 36.6 |
| | Min. | tr | 20.2 | 31.0 | 50.5 | 22.4 |
| | Average | tr | 33.0 | 52.0 | 61.8 | 27.7 |
| > 100μ, in diameter % | Max. | 99.5 | 70.0 | 26.5 | 26.0 | 66.6 |
| | Min. | 80.0 | 17.0 | 2.0 | 3.8 | 39.5 |
| | Average | 94.5 | 36.6 | 17.8 | 9.7 | 56.8 |
| Sorting coefficient (So) | Max. | 1.6 | 9.5 | 8.7 | 8.2 | 6.5 |
| | Min. | 1.3 | 2.6 | 3.7 | 3.2 | 3.9 |
| | Average | 1.4 | 5.7 | 6.3 | 5.7 | 4.8 |
| Quartile skewness (Sk) | Max. | 1.04 | 0.75 | 1.61 | 1.67 | 0.39 |
| | Min. | 1.00 | 0.24 | 0.36 | 0.90 | 0.29 |
| | Average | 1.03 | 0.52 | 0.90 | 1.27 | 0.34 |
| Specific gravity | Max. | 2.68 | 2.70 | 2.69 | 2.64 | 2.59 |
| | Min. | 2.46 | 2.49 | 2.39 | 2.28 | 2.55 |
| | Average | 2.61 | 2.59 | 2.53 | 2.56 | 2.57 |

2. Mechanical properties

In the mechanical analysis, the fractions coarser than 110μ were sieved through the standard sieve, and the sedimentation method was used to analyse the fractions finer than 70μ . The sediments were soaked in distilled water to remove salts, in order to prevent the agglomeration of fine particles. The results obtained are shown in Table 2. Furthermore, Fig. 10 shows a typical change of mechanical pro-

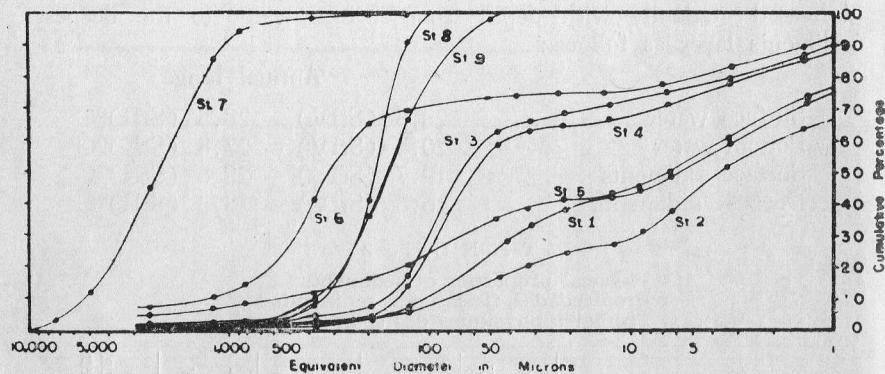


Fig. 10 — Cumulative curves of mechanical analysis in various types of sediments
Curvas cumulativas de análises mecânicas em vários tipos de sedimentos
Courbes cumulatives analyses granulométriques dans différents types de sédiments

perties of sediments from outer area to inner area of the bay.

The area is divided into five subareas according to topography as follows: the outer area of the bay, the area near the mouth of the bay, the central area in the bay, the inner area in the bay, and the area near the Tõna canal.

The textural properties of the sediments in the outer area of the bay are quite different from the sediments in the bay, because the bottom in the outer area is composed of sand and is well sorted.

In the bay, the accumulation of grains finer than 10μ increases gradually from the mouth of the bay to the inner area in the bay except in the vicinity of Tõna Canal. (Fig. 11).

a. The outer area of the bay

Examination shows that the sediments have a median diameter greater than 160μ , and that they are well sorted indicating S_o ranging 1.3 — 1.6. It is remarkable that sediments in this region rarely have fractions finer than 10μ .

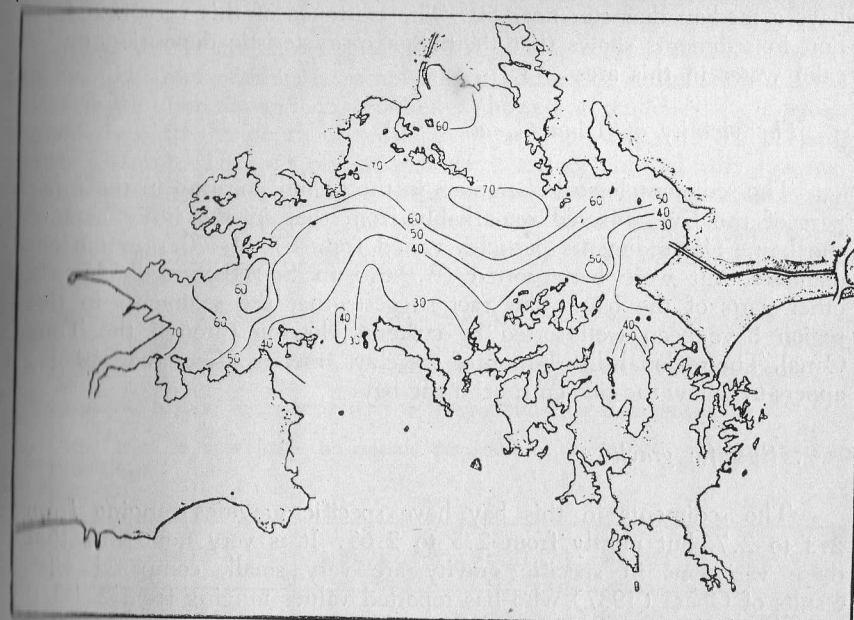


Fig. 11 — Horizontal distribution of fine fraction (less than 10μ)%
Distribuição horizontal das frações finas (menor que 10μ)%
Répartition horizontale de la fraction fine (plus petit que 10μ)%

b. The area in the vicinity of mouth of the bay

In the major part of the area situated in the channels, where the water movement is complicated due to the tide, the median diameters were generally finer than 100μ and the sorting coefficient (S_o) averaged 5.6. Both coarse and fine fractions are well represented, but the finer fraction is poorly sorted. This may indicate that the finer fractions of sediments in this region are not only transported by the strong tide current, but are also deposited on the bottom during slack water.

c. The central area in the bay

The sediments particles in this region have a median diameter near 10μ and appear relatively less sorted than sediments in the former regions. Moreover, it is noticeable that the contents of the silts and fractions finer than 100μ decrease more than in sediments near mouth of the bay.

d. The inner area of the bay

The sediments in this region are extremely poorly sorted, and

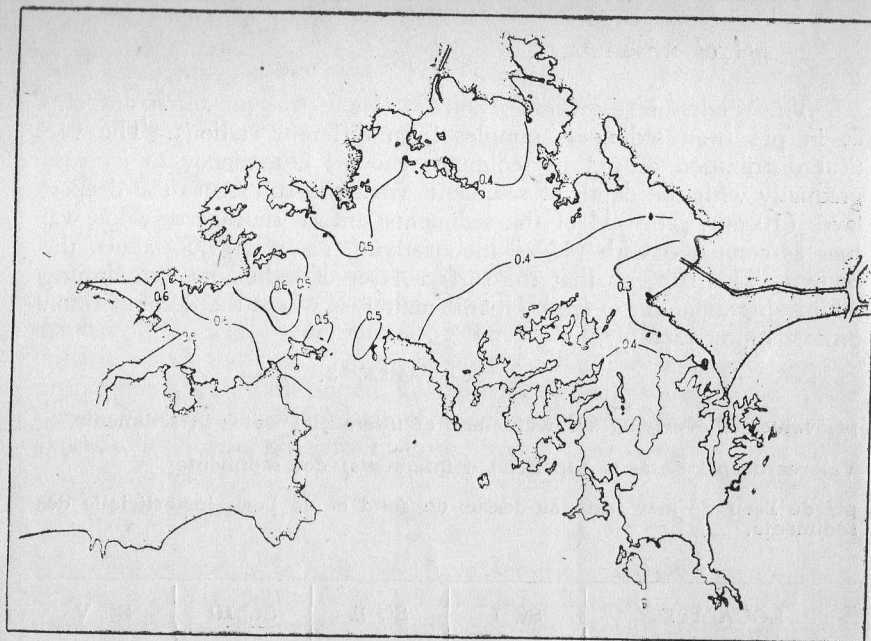


Fig. 12 — Horizontal distribution of total phosphorus in sediments %
Distribuição horizontal de fósforo total nos sedimentos %
Répartition horizontale du phosphore total les sédiments %

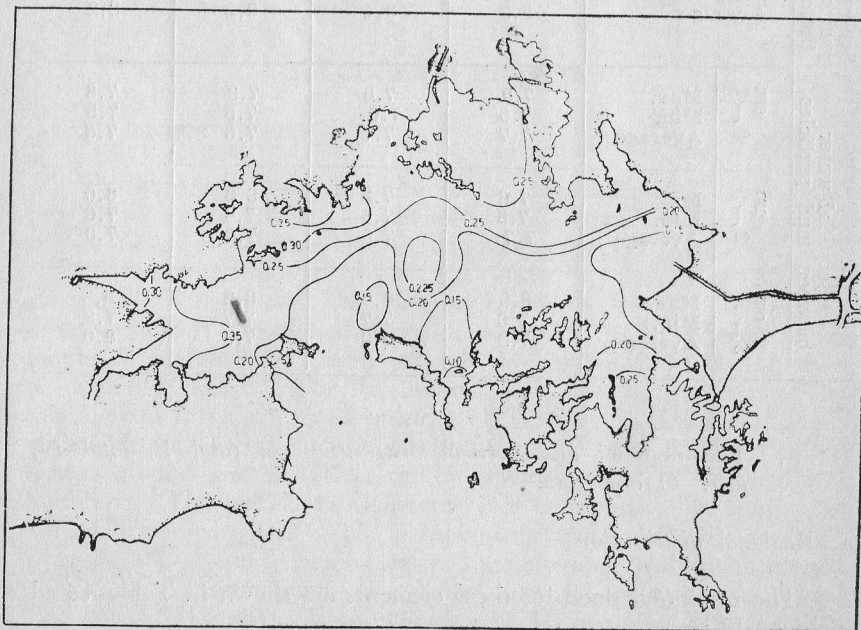


Fig. 13 — Horizontal distribution of total nitrogen in sediments %
Distribuição horizontal de nitrogênio total nos sedimentos %
Répartition horizontale de l'azote total dans les sédiments %

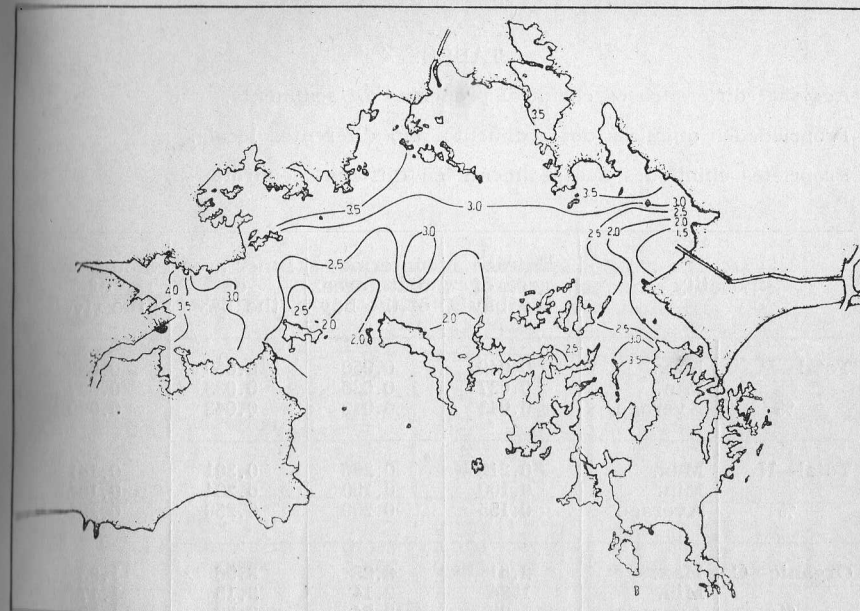


Fig. 14 — Horizontal distribution of organic carbon in sediments %
Distribuição horizontal de carbono orgânico nos sedimentos %
Répartition horizontale du carbone organique dans les sédiments %

org.-C and total sulfide were highest in the inner region of the bay and lowest near the mouth. However, these values in the vicinity of Tōna Canal locating in the inner part of the bay were low similar to those in the mouth of the bay.

On the other hand, total phosphorus showed no great regional difference in various parts of the bay, except that it was very low in the Tōna region.

The distribution of these elements is noteworthy in that lower concentrations of total-P and total-N were found in the south-eastern part of the bay, while they were abundant in Shiogama Harbor. Total-N, org.-C, total-S were fairly high in the central part of the bay. This latter distribution may be due to eddies.

b. Vertical distribution

As to the vertical distribution of organic matter in sediments, many investigations have shown that the organic matter content was more abundant in the surface layer and less in the deeper layers. [Sugawara (1939), Hogetsu (1949), Revell and Shepard (1939), Waksman, et al (1939), Reuzer (1933), Moor (1930), Okuda (1953, 1955)].

TABLE. 4

Regional difference of chemical properties of sediments.

Propriedades químicas dos sedimentos em diferentes locais.

Propriétés chimiques des sédiments en différents endroits.

| Locality | | Entrance area of the bay | Intermediate area of the bay | Inner area of the bay | Mouth area of the river |
|----------------|---------|--------------------------|------------------------------|-----------------------|-------------------------|
| Total—P % | Max. | 0.049 | 0.050 | 0.050 | 0.032 |
| | Min. | 0.037 | 0.036 | 0.033 | 0.027 |
| | Average | 0.043 | 0.042 | 0.043 | 0.029 |
| Total—N % | Max. | 0.212 | 0.266 | 0.301 | 0.141 |
| | Min. | 0.100 | 0.150 | 0.204 | 0.104 |
| | Average | 0.155 | 0.209 | 0.258 | 0.121 |
| Organic—C % | Max. | 2.51 | 3.25 | 3.96 | 1.95 |
| | Min. | 1.34 | 2.14 | 3.15 | 1.17 |
| | Average | 1.95 | 2.74 | 3.52 | 1.58 |
| Total—S % | Max. | 0.056 | 0.102 | 0.137 | 0.039 |
| | Min. | 0.011 | 0.018 | 0.049 | 0.036 |
| | Average | 0.026 | 0.049 | 0.069 | 0.038 |
| N/P | Max. | 4.0 | 6.2 | 7.1 | 4.4 |
| | Min. | 2.5 | 3.9 | 5.2 | 3.6 |
| | Average | 3.3 | 4.9 | 6.1 | 4.1 |
| C/N | Max. | 14.8 | 16.5 | 16.9 | 13.8 |
| | Min. | 11.5 | 11.5 | 12.5 | 11.2 |
| | Average | 12.7 | 13.3 | 13.8 | 12.9 |

Observations were made on the vertical distribution of chemical properties in sediments seasonally from December 1952 to February 1955. The collections of sediments were made once a month and the collected cores were divided into six layers from surface to a depth of 40 cm. Table 5-10 show the results of these observations from April of 1953 and March of 1954.

The maximum value of total—N and total—P was generally obtained in the surface layer and decreased with increasing sediments depth. Furthermore, the vertical decline rate of the three elements was high in the upper layer than 10 cm, as compared with that in the deepest layer.

The vertical distribution of organic carbon at StII, IV and V was

TABLE 5.

Vertical distribution of chemical properties of sediments (St. I)

Distribuição vertical das propriedades químicas dos sedimentos (St. I)

Distribution verticale des propriétés chimiques des sédiments (St. I)

| Depth of mud in cm | | Total—P% | Total—N% | Organic—C% | N/P | C/N | C/P |
|--------------------|---------|----------|----------|------------|------|------|------|
| 0 ~ 0.5 | Max. | 0.063 | 0.282 | 3.28 | 5.0 | 12.8 | 56 |
| | Min. | 0.052 | 0.200 | 2.23 | 3.5 | 10.6 | 39 |
| | Average | 0.056 | 0.249 | 2.87 | 4.46 | 11.5 | 51.3 |
| 0.5 ~ 5 | Max. | 0.065 | 0.254 | 3.38 | 4.7 | 13.6 | 59 |
| | Min. | 0.050 | 0.205 | 2.47 | 3.8 | 11.1 | 46 |
| | Average | 0.054 | 0.231 | 2.86 | 4.30 | 12.3 | 53.0 |
| 5 ~ 10 | Max. | 0.059 | 0.236 | 3.33 | 5.1 | 15.7 | 68 |
| | Min. | 0.044 | 0.150 | 2.27 | 3.1 | 12.0 | 46 |
| | Average | 0.049 | 0.210 | 2.81 | 4.31 | 13.4 | 57.3 |
| 10 ~ 20 | Max. | 0.056 | 0.233 | 3.08 | 4.7 | 16.7 | 70 |
| | Min. | 0.044 | 0.148 | 2.47 | 3.1 | 11.9 | 50 |
| | Average | 0.047 | 0.204 | 2.76 | 4.32 | 13.7 | 58.5 |
| 20 ~ 30 | Max. | 0.049 | 0.206 | 3.43 | 5.7 | 16.7 | 95 |
| | Min. | 0.036 | 0.146 | 2.36 | 3.7 | 12.3 | 52 |
| | Average | 0.043 | 0.188 | 2.69 | 4.43 | 14.4 | 64.1 |
| 30 ~ 40 | Max. | 0.041 | 0.207 | 3.75 | 5.8 | 20.2 | 104 |
| | Min. | 0.035 | 0.146 | 2.32 | 3.8 | 15.0 | 63 |
| | Average | 0.037 | 0.173 | 2.99 | 4.75 | 17.3 | 82.0 |

TABLE 6.

Vertical distribution of chemical properties of sediments (St. II).
Distribuição vertical das propriedades químicas dos sedimentos (St. II).
Distribution verticale des propriétés chimiques des sédiments (St. II).

| Depth of mud in cm | | Total—P% | Total—N% | Organic—C % | N/P | C/N | C/P |
|--------------------|---------|----------|----------|----------------|------|------|------|
| 0 ~ 0.5 | Max. | 0.069 | 0.536 | 8.07 | 8.6 | 15.4 | 120 |
| | Min. | 0.054 | 0.420 | 4.43 | 6.4 | 9.8 | 69 |
| | Average | 0.062 | 0.464 | 5.46 | 7.49 | 11.7 | 87.9 |
| 0.5 ~ 5 | Max. | 0.060 | 0.429 | 4.51 | 7.6 | 12.4 | 87 |
| | Min. | 0.048 | 0.322 | 3.37 | 6.6 | 9.4 | 69 |
| | Average | 0.052 | 0.368 | 4.01 | 7.07 | 10.9 | 77.2 |
| 5 ~ 10 | Max. | 0.054 | 0.363 | 4.21 | 7.4 | 12.0 | 86 |
| | Min. | 0.043 | 0.297 | 3.49 | 6.3 | 10.2 | 64 |
| | Average | 0.048 | 0.333 | 3.80 | 6.94 | 11.4 | 79.5 |
| 10 ~ 20 | Max. | 0.045 | 0.304 | 3.59 | 7.4 | 13.5 | 92 |
| | Min. | 0.036 | 0.261 | 3.15 | 5.9 | 10.8 | 76 |
| | Average | 0.042 | 0.278 | 3.43 | 6.70 | 12.4 | 83.0 |
| 20 ~ 30 | Max. | 0.044 | 0.274 | 3.78 | 7.3 | 14.7 | 99 |
| | Min. | 0.033 | 0.239 | 3.18 | 6.0 | 11.9 | 84 |
| | Average | 0.039 | 0.255 | 3.48 | 6.59 | 13.6 | 89.7 |
| 30 ~ 40 | Max. | 0.043 | 0.262 | 3.76 | 7.3 | 15.2 | 101 |
| | Min. | 0.032 | 0.218 | 2.94 | 5.3 | 12.6 | 81 |
| | Average | 0.038 | 0.240 | 3.39 | 6.43 | 14.1 | 92.0 |

TABLE 7.

Vertical distribution of chemical properties of sediments (St. III).
Distribuição vertical das propriedades químicas dos sedimentos (St. III).
Distribution verticale des propriétés chimiques des sédiments (St. III).

| Depth of mud in cm | | Total—P% | Total—N% | Organic—C % | N/P | C/N | C/P |
|--------------------|---------|----------|----------|----------------|------|------|------|
| 0 ~ 0.5 | Max. | 0.074 | 0.291 | 3.48 | 4.3 | 12.9 | 50 |
| | Min. | 0.057 | 0.236 | 2.78 | 3.6 | 10.6 | 38 |
| | Average | 0.067 | 0.258 | 2.98 | 3.89 | 11.5 | 44.9 |
| 0.5 ~ 5 | Max. | 0.067 | 0.270 | 3.72 | 4.6 | 15.2 | 65 |
| | Min. | 0.055 | 0.220 | 2.73 | 3.3 | 10.5 | 43 |
| | Average | 0.058 | 0.240 | 2.95 | 4.13 | 12.3 | 50.7 |
| 5 ~ 10 | Max. | 0.053 | 0.244 | 3.79 | 5.5 | 17.5 | 77 |
| | Min. | 0.041 | 0.173 | 2.62 | 3.9 | 12.2 | 56 |
| | Average | 0.045 | 0.213 | 2.94 | 4.72 | 13.9 | 65.0 |
| 10 ~ 20 | Max. | 0.062 | 0.224 | 4.06 | 5.5 | 19.8 | 107 |
| | Min. | 0.037 | 0.184 | 2.86 | 3.5 | 13.7 | 49 |
| | Average | 0.044 | 0.208 | 3.30 | 4.88 | 15.9 | 77.8 |
| 20 ~ 30 | Max. | 0.043 | 0.222 | 3.98 | 6.4 | 18.0 | 112 |
| | Min. | 0.034 | 0.192 | 2.85 | 5.0 | 13.3 | 71 |
| | Average | 0.038 | 0.212 | 3.34 | 5.66 | 15.8 | 89.3 |
| 30 ~ 40 | Max. | 0.037 | 0.247 | 4.10 | 7.5 | 18.0 | 118 |
| | Min. | 0.033 | 0.192 | 2.81 | 5.4 | 13.1 | 81 |
| | Average | 0.035 | 0.218 | 3.28 | 6.31 | 15.2 | 95.2 |

TABLE 8.

Vertical distribution of chemical properties of sediments (St. IV).
Distribuição vertical das propriedades químicas dos sedimentos (St. IV).
Distribution verticale des propriétés chimiques des sédiments (St. IV).

| Depth of mud in cm | | Total—P% | Total—N% | Organic—C% | N/P | C/N | C/P |
|--------------------|---------|----------|----------|------------|------|------|------|
| 0 ~ 0.5 | Max. | 0.071 | 0.611 | 4.87 | 10.9 | 14.8 | 93 |
| | Min. | 0.043 | 0.269 | 3.50 | 4.5 | 8.0 | 54 |
| | Average | 0.055 | 0.397 | 4.14 | 7.77 | 10.4 | 77.0 |
| 0.5 ~ 5 | Max. | 0.051 | 0.456 | 4.16 | 8.9 | 17.4 | 103 |
| | Min. | 0.040 | 0.224 | 3.45 | 5.6 | 9.6 | 73 |
| | Average | 0.044 | 0.305 | 3.81 | 6.93 | 12.8 | 87.6 |
| 5 ~ 10 | Max. | 0.048 | 0.367 | 4.51 | 8.0 | 18.1 | 98 |
| | Min. | 0.037 | 0.210 | 3.22 | 5.2 | 12.3 | 70 |
| | Average | 0.042 | 0.242 | 3.63 | 5.82 | 15.2 | 87.5 |
| 10 ~ 20 | Max. | 0.049 | 0.270 | 4.10 | 6.1 | 18.6 | 105 |
| | Min. | 0.039 | 0.209 | 3.46 | 4.5 | 15.3 | 75 |
| | Average | 0.043 | 0.232 | 3.81 | 5.44 | 16.5 | 89.7 |
| 20 ~ 30 | Max. | 0.050 | 0.243 | 4.10 | 6.1 | 17.4 | 105 |
| | Min. | 0.039 | 0.216 | 2.68 | 4.6 | 12.4 | 62 |
| | Average | 0.044 | 0.220 | 3.52 | 5.18 | 15.4 | 79.9 |
| 30 ~ 40 | Max. | 0.054 | 0.247 | 3.82 | 5.3 | 17.0 | 88 |
| | Min. | 0.043 | 0.216 | 3.20 | 4.5 | 13.4 | 66 |
| | Average | 0.047 | 0.234 | 3.55 | 4.9 | 15.2 | 75.3 |

TABLE 9.

Vertical distribution of chemical properties of sediments (St. V).
Distribuição vertical das propriedades químicas dos sedimentos (St. V).
Distribution verticale des propriétés chimiques des sédiments (St. V).

| Depth of mud in cm | | Total—P% | Total—N% | Organic—C% | N/P | C/N | C/P |
|--------------------|---------|----------|----------|------------|------|------|------|
| 0 ~ 0.5 | Max. | 0.065 | 0.701 | 5.24 | 12 | 12.1 | 89 |
| | Min. | 0.046 | 0.260 | 3.07 | 4.6 | 7.5 | 54 |
| | Average | 0.054 | 0.383 | 3.74 | 7.10 | 10.1 | 69.2 |
| 0.5 ~ 5 | Max. | 0.053 | 0.324 | 3.79 | 6.9 | 15.6 | 88 |
| | Min. | 0.040 | 0.212 | 3.01 | 4.5 | 11.0 | 57 |
| | Average | 0.045 | 0.261 | 3.43 | 5.78 | 13.3 | 76.5 |
| 5 ~ 10 | Max. | 0.055 | 0.256 | 3.88 | 5.4 | 18.4 | 91 |
| | Min. | 0.039 | 0.182 | 2.84 | 3.8 | 11.4 | 59 |
| | Average | 0.044 | 0.213 | 3.34 | 4.87 | 15.8 | 76.6 |
| 10 ~ 20 | Max. | 0.044 | 0.268 | 3.87 | 6.1 | 18.5 | 93 |
| | Min. | 0.037 | 0.202 | 2.98 | 4.8 | 11.2 | 68 |
| | Average | 0.041 | 0.219 | 3.41 | 5.35 | 15.7 | 83.8 |
| 20 ~ 30 | Max. | 0.050 | 0.241 | 4.06 | 6.2 | 17.7 | 103 |
| | Min. | 0.035 | 0.196 | 2.90 | 4.2 | 13.8 | 67 |
| | Average | 0.040 | 0.218 | 3.43 | 5.46 | 15.6 | 85.8 |
| 30 ~ 40 | Max. | 0.047 | 0.236 | 3.78 | 6.0 | 17.2 | 103 |
| | Min. | 0.033 | 0.191 | 2.32 | 4.7 | 12.0 | 66 |
| | Average | 0.039 | 0.205 | 3.15 | 5.36 | 15.3 | 81.9 |

TABLE 10

Vertical distribution of chemical properties of sediments at central part of Shiogama harbor.
Distribuição vertical das propriedades químicas dos sedimentos na parte central do porto Shiogama.
Distribution verticale des propriétés chimiques des sédiments dans le centre du port de Shiogama.

| Depth of mud cm. | Total—P% | Total—N% | Organic—C% | N/P | C/N |
|------------------|----------|----------|------------|-----|------|
| 0 ~ 1 | 0.067 | 0.296 | 3.39 | 4.4 | 11.5 |
| 1 ~ 5 | 0.053 | 0.256 | 3.22 | 4.8 | 12.6 |
| 5 ~ 10 | 0.037 | 0.207 | 3.39 | 5.6 | 16.4 |
| 10 ~ 20 | 0.032 | 0.191 | 2.93 | 6.0 | 15.3 |
| 20 ~ 30 | 0.033 | 0.195 | 3.23 | 5.9 | 16.6 |
| 30 ~ 40 | 0.030 | 0.193 | 3.07 | 6.4 | 15.9 |
| 40 ~ 50 | 0.032 | 0.191 | 2.90 | 6.0 | 15.2 |
| 50 ~ 60 | 0.031 | 0.191 | 3.02 | 6.2 | 15.8 |
| 60 ~ 70 | 0.031 | 0.189 | 2.95 | 6.1 | 15.6 |

similar to those of total-N and of total-P described above, but at StI and StIII differed, that is, the maximum content was observed in the deeper layers (in the 30-40 cm layer at StI, and in the 20-30 cm layer in StIII).

As will be seen from Fig. 15, these elements generally decrease vertically in the following order; total-N, total-P and org.-C. This suggests that nitrogen, phosphorus and carbon diffuse into the overlying sea water in that order.

This is in agreement with Waksman's results (1939) on the bacterial decomposition rate of nitrogen and carbon in organic matter.

C. Discussion of Valuer of N/P, and C/N.

1. Regional distribution of N/P and C/N

As will be seen from the Table 4 and Figures 16 and 17, the higher values of N/P and C/N are found in the inner region of the bay than in the mouth of the bay, excepting the vicinity of Tōna.

Features of the distribution of N/P are as follows:

a. An unusually high N/P ratio was found in the central part

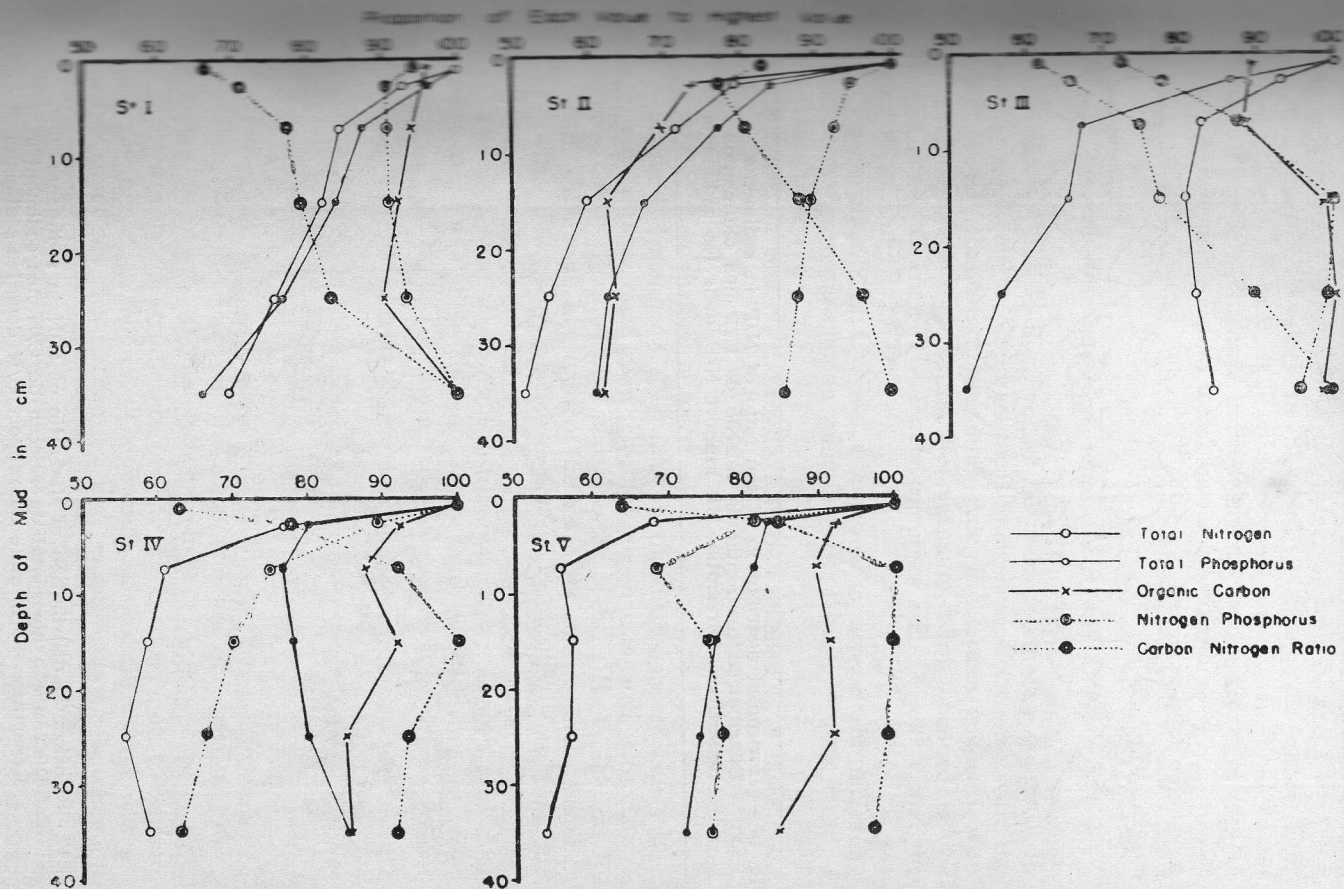


Fig. 15 — Vertical distribution of total nitrogen, total phosphorus, organic carbon, and their ratios in sediments
 Distribuição vertical de nitrogênio total, carbono orgânico, fósforo total e suas relações nos sedimentos
 Répartition verticale de l'azote total, phosphore total, carbone organique et de leurs rapports dans les sédiments

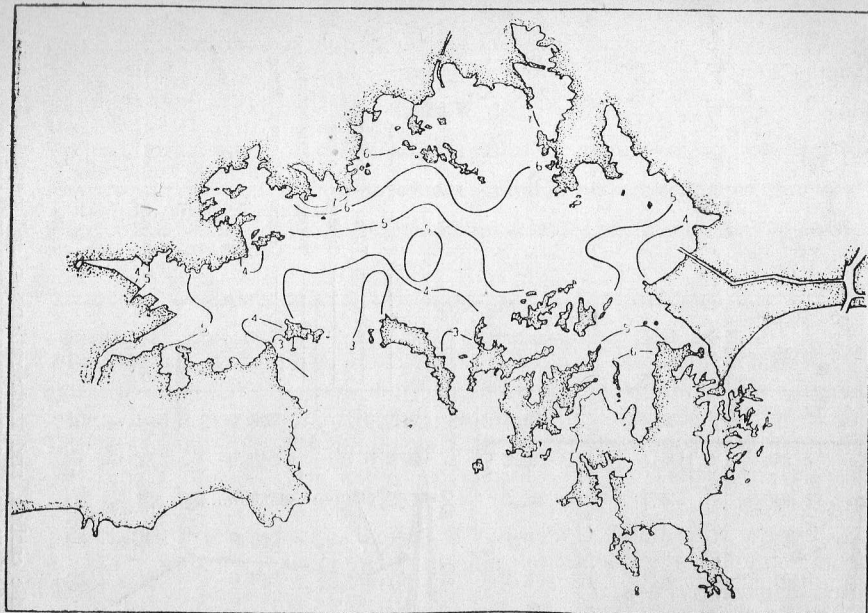


Fig. 16 — Horizontal distribution of the ratio of N/P in sediments
Distribuição horizontal da relação de N/P nos sedimentos
Répartition horizontale du rapport N/P dans les sédiments

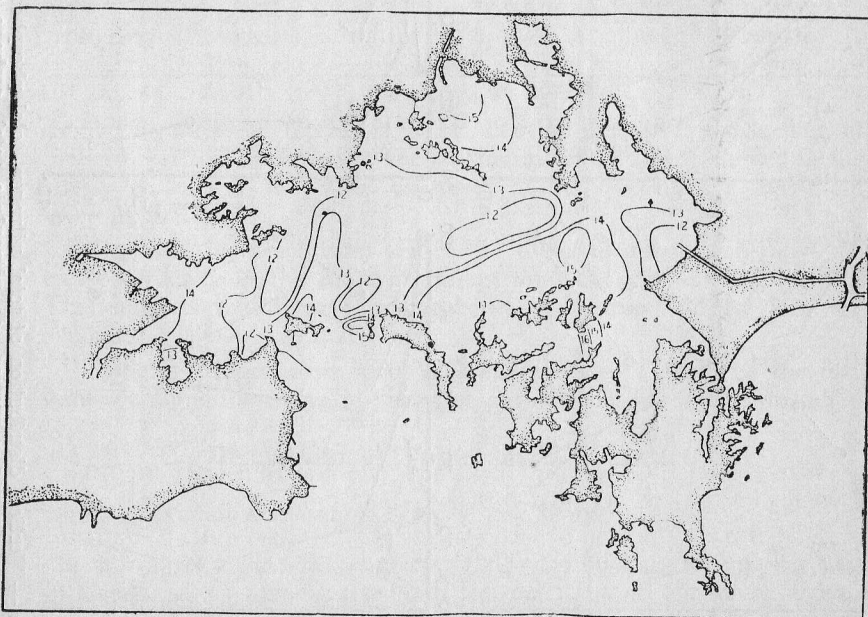


Fig. 17 — Horizontal distribution of the ratio of C/N in sediments
Distribuição horizontal da relação de C/N nos sedimentos
Répartition horizontale du rapport C/N dans les sédiments

of the bay, and was apparently caused by a high accumulation of nitrogenous substances judging from the values of both N and P.

b. The N/P values in Shioyama Harbor were rather low.

c. The C/P ratio, in the bay appears larger than Trask's ratio 8-12 or about 10. This may indicate that the accumulation of organic matter has been proceeding under favourable conditions.

d. In the *Zostera* zone, N/P ratio was relatively high while that of C/N was relatively low.

2. Vertical distribution of ratios, N/P and C/N

Vertically, the N/P ratio may be divided into two groups. In one the maximum is found in the surface layer decreasing with the depth of the sediments in the other type, it increases gradually with depth from the surface layer, the maximum being obtained in the deepest layer (40 cm). The former comprises StII, IV and V and the latter of StI and III.

On the other hand, C/N values appeared to increase with increasing depth, although the maximum value in StIII, IV and V were found in intermediate layers.

At StII, IV and V, the results may be explained by a more rapid reduction of nitrogen than phosphorus (see Fig. 15).

On the other hand, at StI and III, the reduction of phosphorus was greater than that of nitrogen.

In like the manner C/N values in the deeper layers were rather high, due to more rapid reduction of nitrogen compared with that of carbon. The N/P value increased in order of StI, III, V, IV and II, however, there was no trend of C/N values among these stations. C/P values showed a tendency to increase with the depth from the surface.

The results on the vertical distribution of N., C., P. and their ratio indicate that these elements return into the overlying sea water in order of N, P. and C during the decomposition of organic matter in sediments.

3. Total-N, P, C and their ratios in the particle fraction of different size of sediments

The author in a previous paper (Okuda and Sato, 1955) reported a positive correlation between the amount of the fine fraction (10 μ) in sediments and the organic carbon content.

To estimate the significance of N/P, C/N, the N, P, C contents were determined as follows: The fraction coarser than 10 μ was separated from the fine fraction by the beaker method, the chemical analyses were made on the coarse fraction and the original sample. The contents of these elements in the fine fraction were computed by the following formula.

$$N_f = \frac{1. N_t - C. N_c}{F}$$

- Nt The content of total nitrogen (or org.-C, total-P) in the original sample.
 Nc The content of total nitrogen (or org.-C, total-P) in the coarse fraction
 Nf The content of total nitrogen (or org.-C, total-P) in the fine fraction.
 C The content of the coarse fraction.
 F The content of the fine fraction.

The contents of N, P, C and N/P in the fine fraction were higher compared with those in the coarse fraction, except for the total phosphorus content at St 109 and N/P at St 108. On the other hand, the values of C/N in the coarse fractions were generally higher than in the fine fraction except at St 101 and St 109. (Table 11)

4. Discussion on the values of N/P and C/N

In the ocean, the principal source of the organic matter in sediments is the remains of organisms, especially of plankton.

If the organic matter in the collected sediments have not been decomposed at all, the N/P and C/N of the organic matter in sediments should be the same as those in the sea water. Since the organic matter in the sediments are decomposed by the action of bacteria after its deposition, the N/P and C/N in the sediments may differ from those in the sea water, because the rate of decomposition may differ among these elements (N, P and C). The values of N/P and C/N in sediments appear to indicate how much the organic matter in sediments have been decomposed.

Considerable attention has been paid by many investigators to the ratio of carbon to nitrogen, C/N. On the other hand, the ratio of nitrogen to phosphorus, N/P in the sediments has not been given much attention, although that in the sea water and in the plankton have been investigated by Redfield (1934) and Cooper (1934, 1937 and 1939). The contents of phosphorus, nitrogen and carbon in plankton were reported by many investigators and have been summarized by Sverdrup, Johnson and Fleming (1946) and Harvey (1955). N/P and C/N calculated from these results are as follows: N/P ranging from 6.7 - 13 but mostly near 7; and C/N ranging from 4.0 to 7.2 but mostly near 6.

Results in many planktons and nektons by Matsudaira and Tsuda (1956) show that N/P varies between 6.8 and 9.2 and C/N varies from 4.9 to 6.6. In addition, the author has obtained N/P ranging from 4.0 to 16 and averaging 6.7 from plankton collected from Matsushima Bay.

TABLE 11

Chemical properties in coarser and finer parts of sediments.
 Propriedades químicas das frações finas e grossas dos sedimentos.
 Propriétés chimiques des sédiments dans la fraction fine et la fraction grossière.

| Locality | Particle size | Total-P % | Total-N % | Organic-C % | N/P | C/N |
|----------|---------------|--------------|--------------|----------------|-----|------|
| 101 | Whole | 0.050 | 0.197 | 2.71 | 3.9 | 13.8 |
| | 10 u >> | 0.060 | 0.257 | 3.57 | 4.3 | 13.9 |
| | 10 u >> | 0.043 | 0.155 | 2.10 | 3.6 | 13.5 |
| 102 | Whole | 0.039 | 0.184 | 2.39 | 4.7 | 13.0 |
| | 10 u >> | 0.054 | 0.307 | 3.64 | 5.7 | 11.9 |
| | 10 u >> | 0.030 | 0.108 | 1.62 | 3.6 | 15.0 |
| 103 | Whole | 0.041 | 0.274 | 3.55 | 6.7 | 13.0 |
| | 10 u >> | 0.046 | 0.316 | 3.77 | 6.9 | 11.9 |
| | 10 u >> | 0.036 | 0.229 | 3.31 | 6.4 | 14.5 |
| 104 | Whole | 0.034 | 0.184 | 2.23 | 5.4 | 12.6 |
| | 10 u >> | 0.036 | 0.253 | 2.88 | 7.0 | 11.4 |
| | 10 u >> | 0.031 | 0.095 | 1.60 | 3.1 | 16.8 |
| 105 | Whole | 0.030 | 0.140 | 2.00 | 4.7 | 14.3 |
| | 10 u >> | 0.032 | 0.296 | 3.22 | 9.3 | 10.9 |
| | 10 u >> | 0.029 | 0.076 | 1.50 | 2.6 | 19.7 |
| 106 | Whole | 0.041 | 0.256 | 3.57 | 6.2 | 13.9 |
| | 10 u >> | 0.045 | 0.297 | 3.72 | 6.6 | 12.5 |
| | 10 u >> | 0.036 | 0.201 | 3.37 | 5.6 | 16.8 |
| 107 | Whole | 0.048 | 0.198 | 2.51 | 4.1 | 12.7 |
| | 10 u >> | 0.052 | 0.242 | 2.58 | 4.7 | 10.7 |
| | 10 u >> | 0.044 | 0.158 | 2.45 | 3.6 | 15.5 |
| 108 | Whole | 0.058 | 0.332 | 4.00 | 5.7 | 12.0 |
| | 10 u >> | 0.065 | 0.345 | 4.11 | 5.3 | 11.9 |
| | 10 u >> | 0.048 | 0.312 | 3.83 | 6.5 | 12.3 |
| 109 | Whole | 0.057 | 0.242 | 3.05 | 4.2 | 12.6 |
| | 10 u >> | 0.056 | 0.271 | 3.49 | 4.8 | 12.9 |
| | 10 u >> | 0.058 | 0.197 | 2.37 | 3.4 | 12.0 |

Few investigations have been made on the N/P and C/N in the benthic animals which are "Consumer" and "Supplier" of the organic matter in the sediments. The author has attempted to determine these ratios for the benthic animals from Matsushima Bay. These values are shown in Table 12. The results show that N/P varied from 11

TABLE 12

Contents of total—P, total—N, organic—C, and their ratios in benthic animals.
Teor de P—total, N—total, C—Organico e suas relações nos animais bentônicos.
Teneurs en P—total, N—total, C—organique et leurs rapports dans les animaux benthiques.

| Benthic animal | Total—P % | Total—N % | Organic—C % | N/P | C/N |
|--------------------------------|--------------|--------------|----------------|------|------|
| <i>Stenethyra edogawaensis</i> | 0.16 | 1.81 | 6.77 | 11.3 | 3.74 |
| <i>Fluviocingula nipponica</i> | 0.17 | 2.00 | 8.54 | 11.8 | 4.27 |
| <i>Nereis</i> sp. | 0.57 | 7.34 | 35.03 | 12.9 | 4.77 |
| <i>Macoma incongrua</i> | 0.49 | 7.58 | 33.6 | 15.5 | 4.43 |
| <i>Nassarius festivus</i> | 0.083 | 0.896 | 5.58 | 10.8 | 6.23 |

to 16 and C/N ranged between from 3.7 to 6.2. N/P and C/N in the plankton and in the benthic animals which are the principal source of the organic matter in the sediments, show a great difference from those in sediments, that is, N/P of the former is generally higher than that of the latter, while, C/N is the reverse.

It may be concluded that N/P and C/N of sediments are affected more by the content rate of decomposed and undecomposed organic matter, than by the amount of organic matter in sediments. The more the organic matter in sediments are decomposed, the more the N/P and C/N of sediments may differ from those of original organic matter, such as plankton or benthic animal. Such interpretation on N/P and C/N may be supposed by the characteristic distribution of these ratios in sediments in Matsushima Bay as abovementioned, that is; N/P in the finer fraction was higher than that in the coarse fraction, while the C/N of the former was lower. The mouth of the bay and the vicinity of Tōna Canal having lower contents of the finer fraction, showed lower N/P values than that in the inner area of the

bay which has a higher content of the fine fraction. On the other hand, C/N in the former showed rather low values as compared with that in the latter. Vertically, the surface layer showed higher values of N/P and lower values of C/N in comparison with these values in the deeper layers.

D. Soluble Nutrients in Sediments

1. Experimental procedures for determination of the soluble nutrients

Kato (1952) has reported that from about one half to one third of the total organic substances in sediments may be resistant humus. This indicates that only a part of the organic matter in sediments will be concerned with the nutrient metabolism at the bottom.

In order to study dynamically the metabolic circulation of nutrients in the sediments it is important to determine not only the total organic matter but also the soluble nutrients or at least the easily soluble nutrients. In order to test a large number of samples in a short time, (in routine field work) the simplicity and rapidity of analytical method are often more important than a high degree of precision.

With this in mind, the author has attempted the simple determination of soluble silicate—Si, phosphate—P, ammonia—N, nitrite—N and nitrate—N in sediments as follows: Ten grams of fresh raw sediments were placed into a bottle of 350 ml capacity, then 300 ml of artificial sea water (free from the nutrients) were added. This mixture was shaken for three minutes and filtered through N.º 2 Toyo-filter paper. Nutrients in the filtrate were determined by the common method for sea water. Sediments on the filter paper were dried after washing with distilled water and weighed. The quantity of nutrients in sediments was computed per gram of dried sediments. In this experiment, sediments which were brought to the laboratory, were immediately placed in a refrigerator, and analyzed as soon as possible.

Fundamental problems of the extraction of soluble nutrients, were reported by the author in a previous paper (Okuda, 1953).

2. Soluble nutrients in sediments

The origin of the soluble nutrients in sediments differs with different elements, that is, ammonia—N originates from organic matter, and phosphate—P and silicate—Si from both organic matter and mineral matter.

Regarding the condition of soluble nutrients in sediments, the following three conditions may be assumed, namely; (1) The soluble nutrients are adsorbed weakly on the surface of the organic and inorganic colloidal particle which is a principal constituent of sediments. (2) They are soluble in the interstitial water of sediments. (3) They may exist.

insoluble form such as insoluble mineral matter or undecomposed organic mater.

In the author's method (shaking extraction method) above mentioned, as it is impossible to liberate nutrients of type (3), soluble nutrients determined must be derived from types (1) and (2).

To compare the content of soluble nutrients between types (1) and (2), the author attempted the following experiments. The soluble nutrients were estimated in the interstitial water separated by centrifugation from fresh raw sediments (type2). These values are called (B) in this discussion. The results from the shaking extraction method represent types (1) and (2) and are called (A). The difference between A and B corresponds to the content of soluble nutrients of type (1). These results are given in Table 13.

In general, the values in both type (1) and type (2) increased with depth of sediments, with a few exceptions. As seen from the Table 13, phosphate—P of the surface layer at StII and StIII and ammonia—N of the surface layer at StIII, in the interstitial water (B), showed higher values than the whole contents (A). This fact may be caused by experimental error, or by readsorption of these elements during shaking and filtration.

As compared with the values of both (A-B) and (B), the (B) values in the surface layer and the next layer (2-5 cm) showed generally higher values than those in (A-B), however, the (B) values in the deeper layer (5-10 cm) were inverse to the (A-B) values.

These results show that soluble nutrients in sediments obtained by the shaking extraction method may consist of not only those in the interstitial water but also those adsorbed weakly on the surface of the colloidal sediments.

Higher contents of soluble nutrients in the deeper layer in spite of lower contents of organic matter may be due to the following reasons :

(1) As the sediments in deeper layer have been passed for a longer time since deposition, there is a possibility for the formation of soluble nutrients although the decomposition rate of organic matter might be very slow in this layer.

(2) As the sediments in the deeper layer are not in contact with the overlying sea water, the soluble nutrients in this layer have less chance of returning to the overlying water in comparison with those in the surface layer.

3. *Regional distribution of the soluble nutrients in sediments*

In a previous paper (Okuda and Sato 1955), regional distribution of soluble nutrients in sediments in Matsushima Bay was reported as follows :

In general, the lower values of the soluble nutrients in sediments distributed in the south-eastern region in the bay as well as that of

TABLE 13

Distribution of soluble nutrients in sediments (A) and in their interstitial water (B).

Distribuição dos nutrientes solúveis nos sedimentos (A) e na suas águas interesticial (B)

Repartition des éléments nutritifs solubles dans les sédiments (A) et leur eau intersticielle (B)

| St. No. | Depth of mud in cm | Phosphate—P γ /g | | | Ammonia—N γ /g | | | Silicate—Si γ /g | | |
|---------|--------------------|-------------------------|-----|-------|-----------------------|-----|-------|-------------------------|-----|-----|
| | | A | B | A-B | A | B | A-B | A | B | A-B |
| II | 0 ~ 2 | 3.6 | 4.3 | — 0.7 | 8.0 | 12 | — 4.0 | 114 | 99 | 15 |
| | 2 ~ 5 | 5.8 | 5.2 | 0.6 | 26 | 19 | 7.0 | 220 | 110 | 110 |
| | 5 ~ 10 | 5.8 | 3.4 | 2.4 | 20 | 17 | 3.0 | 240 | 120 | 120 |
| III | 0 ~ 2 | 5.4 | 8.4 | — 3.0 | 20 | 9.5 | 10.5 | 166 | 97 | 69 |
| | 2 ~ 5 | 15 | 4.7 | 10.3 | 60 | 7.9 | 52.1 | 124 | 84 | 40 |
| | 5 ~ 10 | 13 | 4.7 | 8.3 | 70 | 11 | 59 | 200 | 74 | 126 |
| V | 0 ~ 2 | 10 | 8.8 | 1.2 | 40 | 28 | 12 | 160 | 100 | 60 |
| | 2 ~ 5 | 14 | 9.7 | 4.3 | 100 | 34 | 66 | 200 | 120 | 80 |
| | 5 ~ 10 | 40 | 15 | 25 | 200 | 58 | 142 | 240 | 120 | 120 |

A... Total amount in 10g of wet mud

B... Amount in interstitial water in 10g of wet mud.

total-P and total-N, and those in Shiogama Harbor showed comparatively high values. However, phosphate-P and ammonia-N in both the Satoura region and the Kunoshima region showed low values, in spite of the rather high values of total-P, total-N and organic-C.

The area showing the comparatively low values in phosphate-P and ammonia-N corresponds to the *Zostera* area. This suggests that the soluble nutrients of sediments in the *Zostera* area may be consumed by the *Zostera* during their growth. This problem will be explained in a later chapter. The reasons for the high values of soluble nutrients in Shiogama Harbor may be because of high precipitation of organic matter on the bottom, where sewage flows from the city. The reason that soluble nutrient contents in the Satoura region differ from those in Shiogama Harbor, may be not only the consumption of these elements by *Zostera* but also because the organic matter of sediment in Shiogama Harbor is composed of sewage and plankton, while, that in the Satoura region may be composed chiefly of the detritus of *Zostera*. Accordingly, the large differences of total-P, total-N and soluble nutrients in both these areas may be attributable to the qualitative differences and the differences of decomposition processes of the organic matter, notwithstanding the approximately equal values of organic matter content of sediments in both areas.

4. Vertical distribution of soluble nutrients in sediments and their seasonal variation

The vertical distribution of soluble nutrients in sediments are shown in Figs. 18–20.

Silicate-Si (Fig. 18)

The difference in silicate-Si content between the stations was very small, compared with those of phosphate-P and ammonia-N. The content of silicate-Si in sediments showed a tendency to increase with the depth in sediments with a few exceptions. The silicate-Si content was lower in the cool season (from November to February) and higher in the warm season.

Phosphate-P, Ammonia-N (Fig. 19 and 20)

There was very large differences in the phosphate-P and ammonia-N contents between the five stations, these elements increased in order of StII, I, III, V and IV. The phosphate-P increased gradually from the surface to the deepest layer. Although high values of phosphate-P were occasionally observed in warm season, there was no distinct tendency toward seasonal variation.

High values of ammonia-N were obtained in summer and there was a greater seasonal variation in the surface layer than in deeper layers.

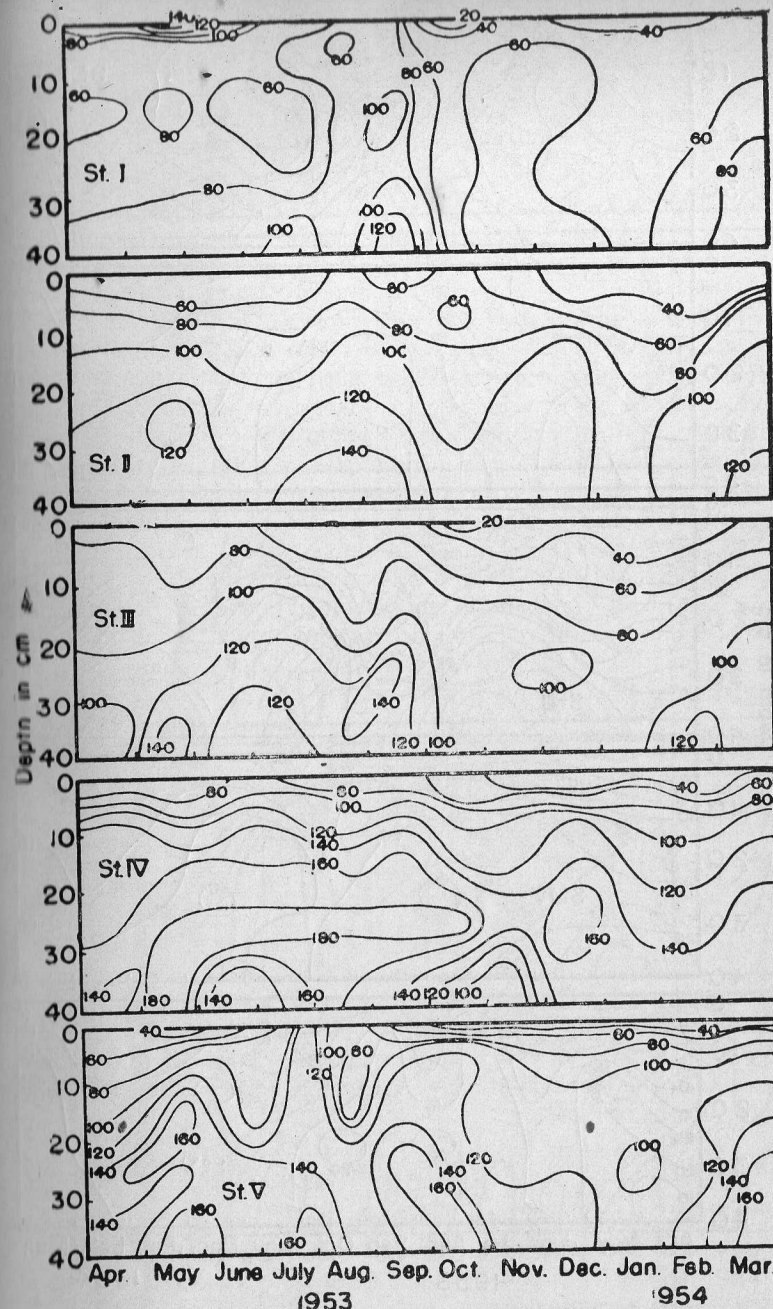


Fig. 18 — Seasonal variation of vertical distribution of silicate-Si in sediments γ/g
 Variação estacional da distribuição vertical de silicato-Si nos sedimentos γ/g
 Variation saisonnière de la repartition verticale du silicate-Si dans les sédiments γ/g

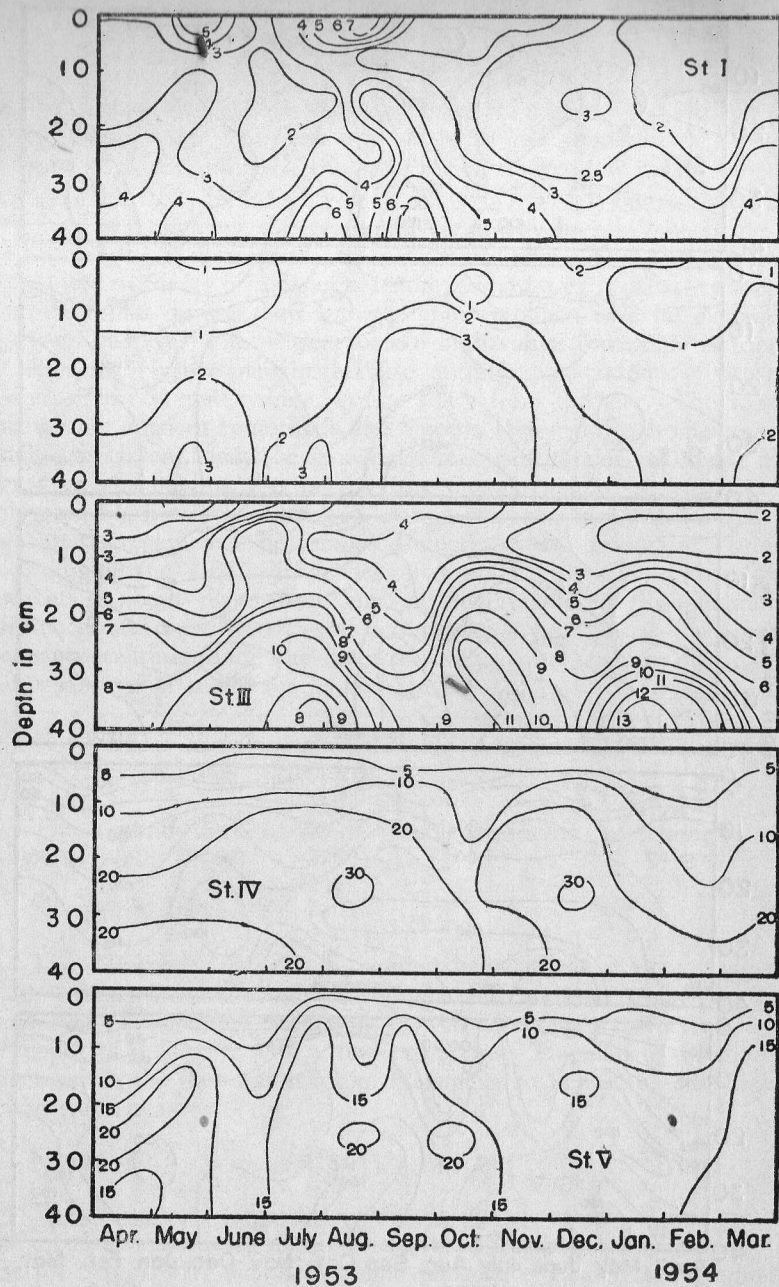


Fig. 19 — Seasonal variation of vertical distribution of phosphate-P in sediments γ/g
 Variação estacional da distribuição vertical do fosfato-P nos sedimentos γ/g
 Variation saisonnière de la répartition verticale du phosphate-P dans les sédiments γ/g

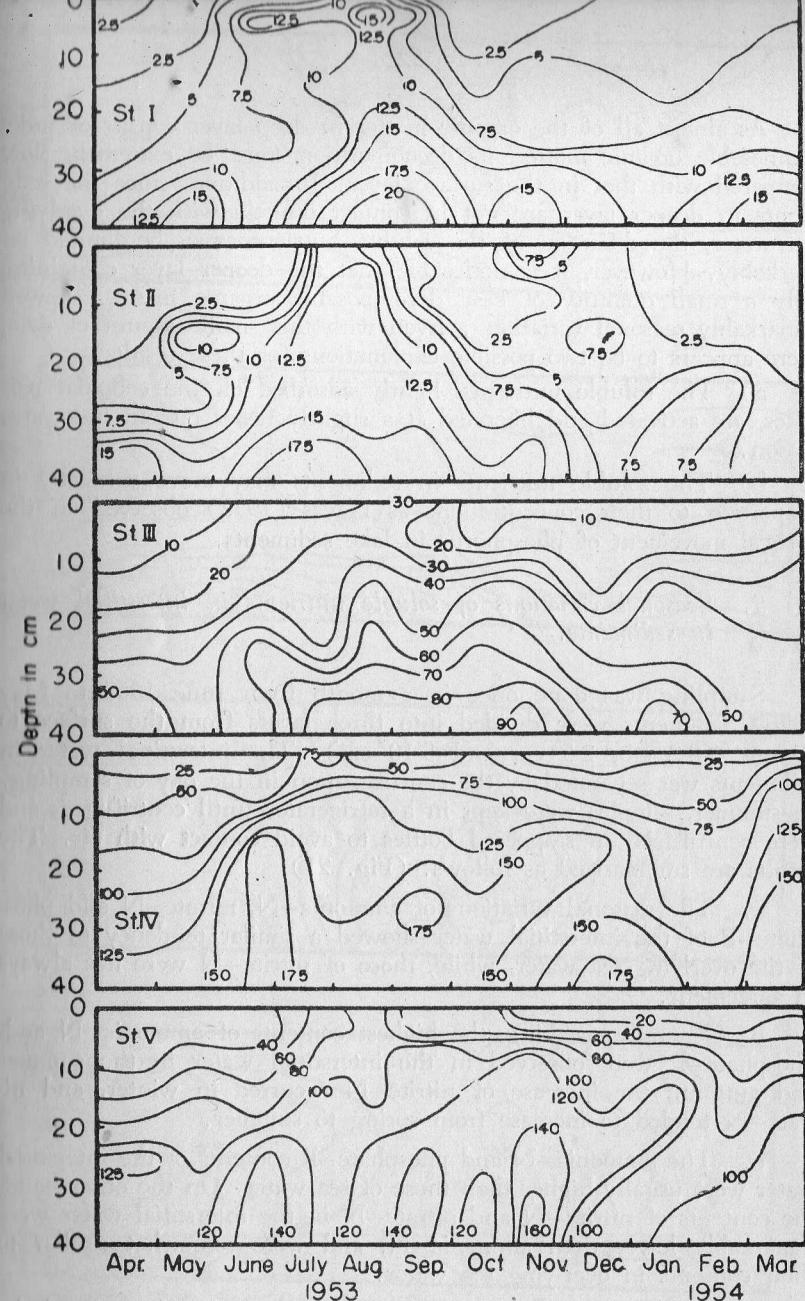


Fig. 20 — Seasonal variation of vertical distribution of ammonia-N in sediments γ/g
 Variação estacional da distribuição vertical de amônia-N nos sedimentos γ/g
 Variation saisonnière de la répartition verticale de l'ammoniac-N dans les sédiments γ/g

As almost all of the organic matter in deep layer consist of indecomposable organic matter, its decomposition must be extremely slow compared with that in the surface layer. In addition, since the sediments in deeper layer are not in contact directly with the overlying sea water, the diffusion of the soluble nutrients may be limited remarkably. However, it is noticeable that the deeper layer containing only a small quantity of easy decomposable organic matter, showed remarkably seasonal variation. Even with this small amount of data, there appears to be two possible explanations for these results.

a) The soluble nutrients, lightly adsorbed on the colloidal particles, are activated and liberated at a slightly faster rate in the warm season.

b) The soluble nutrients in sediments may move vertically in proportion to their concentrations as Hayes (1952) observed on the vertical movement of phosphorus in lake sediments.

5. Seasonal variations of soluble nutrients in interstitial water in sediments.

Sampling was done once in a month from June 1955 to May 1956. Sediments were divided into three layers from the surface to 10 cm. (0-2 cm, 2-5 cm and 5-10 cm). The interstitial water in sediments was separated by the centrifugation in the day of sampling. In summer, samples were kept in a refrigerator until centrifuged, and were centrifuged in stoppered bottles to avoid contact with air. The results are summarized as follows. (Fig. 21)

a. The seasonal variations of ammonia-N, nitrate-N and phosphate-P of the interstitial water showed a similar tendency to those of the overlying sea water, while, those of nitrite-N were not always in agreement.

b. Generally speaking, the highest contents of ammonia-N and phosphate-P were observed in the interstitial water in the summer and autumn, the increase of nitrite-N occurred in winter, and nitrate-N tended to increase from spring to summer.

c. The ammonia-N and phosphate-P contents of the interstitial water were usually higher than those of sea water. On the other hand, the contents of nitrite-N and nitrate-N in the interstitial water were remarkably lower than ammonia-N, and were somewhat similar to their contents in overlying sea water.

d. In the winter season, ammonia-N and phosphate-P of the interstitial water in the surface layer (0-2 cm) were generally lower than those in deeper layers, while in summer, these elements either were higher toward the surface, or did not vary with depth. In general, the content of nitrite-N of the interstitial water increased with depth, and nitrate-N decreased with depth.

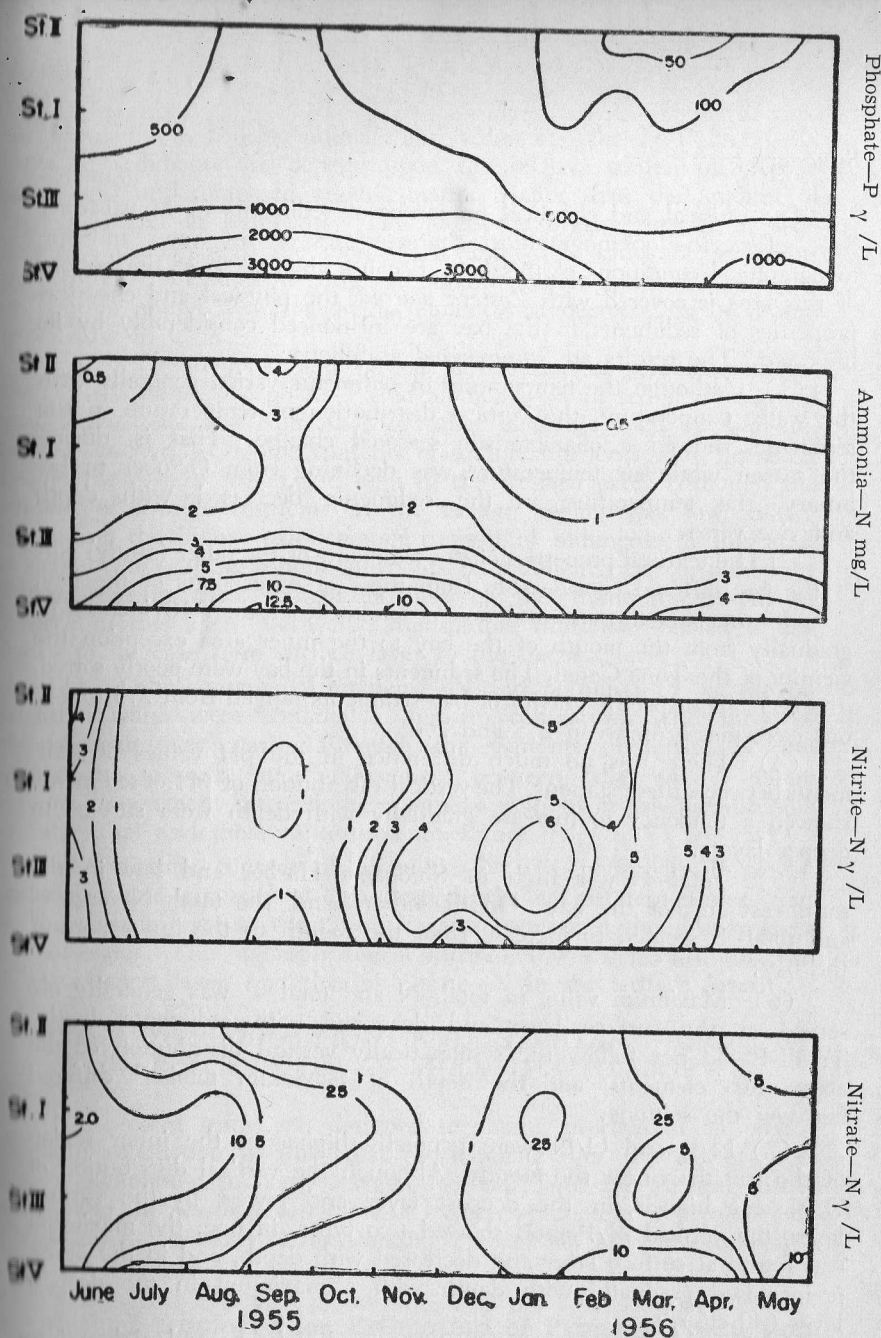


FIG. 21 — Seasonal variation of vertical distribution of inorganic nitrogen and phosphate-P in interstitial water in sediments
 Variação estacional de nitrogênio e fosfato na água intersticial dos sedimentos
 Variation saisonnière de l'azote mineral et du phosphate-P dans l'eau intersticielle des sédiments

Summary

The physical and chemical properties of sediments in Matsushima Bay, reflect the oceanographical characteristics of sea water and the topographical conditions of this bay. Because about 80% of the bottom of this area is covered with *Zostera marina*, the physical and chemical properties of sediments in the bay are influenced considerably by its life-cycle. The results are summarized as follows:

(1) Although the temperature of sediments varied generally with the water temperature, the vertical distribution of temperature in the sediments showed a characteristic seasonal change. That is, during the season while air temperature was declining from October to February, the temperature in the sediments decreased with depth and vice versa.

(2) The textural properties of the sediments of the outer (sandy) part of the bay differed considerably from those of other parts of the bay.

In the bay, the accumulation of grains finer than 10 increased gradually from the mouth of the bay to the inner area except the vicinity of the Tōna Canal. The sediments in the bay were poorly sorted.

(3) The specific gravity of bay sediments ranged from 2.3 to 2.7 but were mostly between 2.5 and 2.65.

(4) There was no much difference in the pH values of sediments between these stations. The vertical distribution of pH of sediments showed a tendency to increase gradually with depth from surface to deeper layers.

(5) Total-P was high in Shiogama Harbor and low in the south-east area of the bay. On the other hand, the total-N, org.-C and total-S seemed to increase from the mouth to the inner part of the bay.

(6) Maximum value in total-N and total-P was generally observed at the surface layer and decreased with sediments depth. Total-P did not follow the systematically vertical distribution of the above two elements, and the depth of maximum total-P differed between the stations.

(7) N/P and C/N were generally higher in the inner region of the bay than near the mouth. Although the vertical distribution of C/N was highest in the deepest layer and lowest in the surface layer, the vertical N/P ratio showed two types, in one, the maximum was found at surface layer and decreased with depth, and in the other, it increased gradually with depth with a maximum in the deepest layer (40 cm).

(8) The diffusion rate of nitrogen, phosphorus and carbon into the overlying sea water during the decomposition process of organic matter in sediments, may occur in that order, judging from the vertical distribution of these elements and their ratios.

(9) From the discussion on N/P and C/N of sediments throughout the comparison of the content of nitrogen, carbon and phospho-

rus in plankton, benthic animals and sediments, the N/P and C/N ratios of sediments are depend upon the relative content of decomposed and undecomposed organic matter, rather than the amount of organic matter in sediments. The more the organic matter in sediments is decomposed, the more N/P and C/N ratios of sediments may differ from those of original organic matter (such as plankton or benthic animal), and show a tendency to decrease in N/P and to increase in C/N.

(10) The regional and vertical distribution of soluble nutrients such as silicate-Si, phosphate-P and ammonia-N in sediments showed a different tendency from that of other elements such as total-N, total-P and org.-C. The contents of soluble nutrients were generally low in the eastern region and high in the western part. Although the content of soluble nutrients in the eastern region was low, notwithstanding the high organic matter content of sediments in this area, it may be that these soluble nutrients of sediments are consumed by *Zostera* during their growth because of the luxuriant growth of *Zostera* in this area. Vertically, the soluble nutrients showed a tendency to increase from surface layer to the deepest layer.

(11) The contents of ammonia-N and phosphate-P of the interstitial water were remarkably high in comparison with those of the overlying sea water, although the contents of nitrite-N and nitrate-N showed little difference between the two. There was good agreement between the seasonal variations of soluble nutrients of interstitial and those of water temperature.

The maxima content of ammonia-N and phosphate-P of interstitial water occurred at different depths at different times, that is, the surface layer at the time of warm water and the deeper layer at cool water. The highest value of nitrite-N was generally observed in the deepest layer, and that of nitrate-N in the surface layer.

V PRIMARY PRODUCTION AND STANDING CROP OF NET PLANKTON IN SHIOGAMA HARBOR

The present study was designed to obtain information on phytoplankton production in this area. To estimate this, the author used Wiley's "light-and-dark bottle oxygen method", and the vertical distribution and the seasonal variations of oxygen production were observed. The seasonal variations of the standing crop of net plankton were also estimated.

A. Method Employed for Estimation of Primary Production

The estimation of primary production was made at two positions in Shiogama Harbor, one in the shallow central part with a depth of 2 to 3 m, and the other one in the inner part with a depth of 4 to 5 m.

The sea water, collected at various depths, was placed into three oxygen bottles. Dissolved oxygen in one of them was fixed by Winkler's method as soon as the sea water was collected, another was covered with black cloth, and third was left uncovered. The latter two bottles were hung at equal depths, for some days, that is, one or two days in summer and five to seven days in winter. They were then removed and the dissolved oxygen was determined.

It was assumed that both photosynthesis and respiration occurred in the uncovered bottle while only respiration took place in the covered one. Thus the respiration value was obtained from the decrease of dissolved oxygen in the covered bottle, the net production from the difference of oxygen in the uncovered bottles, and the gross production was computed from the sum of the respiration value and the net production.

The estimation of primary production was made at water depths of 0, 0.5 and 1.5 m at the central part of the harbor and 0, 0.5, 1.0, 2.0, 3.0 and 4.0 m at the inner part.

B. Results of Primary Production

1. Vertical distribution and seasonal variation of primary production

The results obtained are shown in Fig. 22 and 23. The point of intersection of the curves for gross production and respiration corresponds to the compensation point. In the layer above the compensation point, the positive net production is going on, on the other hand, negative net production is occurring below this point.

The gross production at the central part (St.III) of the harbor was higher than the respiration, except for a few cases in August and November. In other words, positive net production was occurring throughout the entire water column. This may be due to the sun light penetrating to the bottom because of the shallow depth at this part.

In the inner part (St.V), the gross production at the lowest depth was lower than the respiration except in February and March. It was notable that in November, 1956, the respiration showed a higher value than the gross production throughout the entire water column. There was a seasonal variation in the compensation point, ranging from 0.5 to 4 meters but usually between 2 and 3 meters.

The assimilation of phytoplankton may be affected by the light condition, when physical and chemical factors such as water temperature or concentration of plant nutrients are uniform. As the light intensity and its wave length vary with water depth, the photosynthesis of phytoplankton diminishes with the decrease of penetration

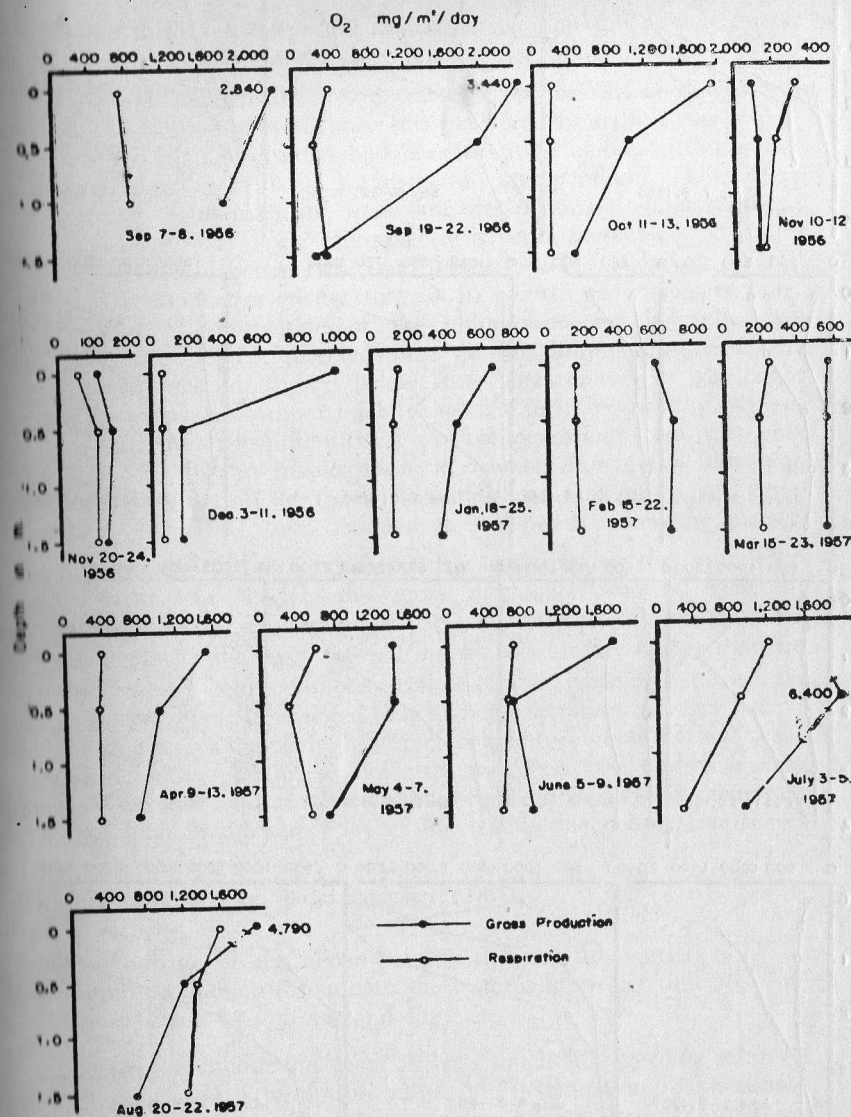


Fig. 22 — Monthly gross production and respiration at every depth of the harbor centre

Produção bruta mensal e respiração em cada profundidade de centro do porto

Valeur mensuelle de la production brute et de la respiration à toutes profondeurs de la partie centrale du port

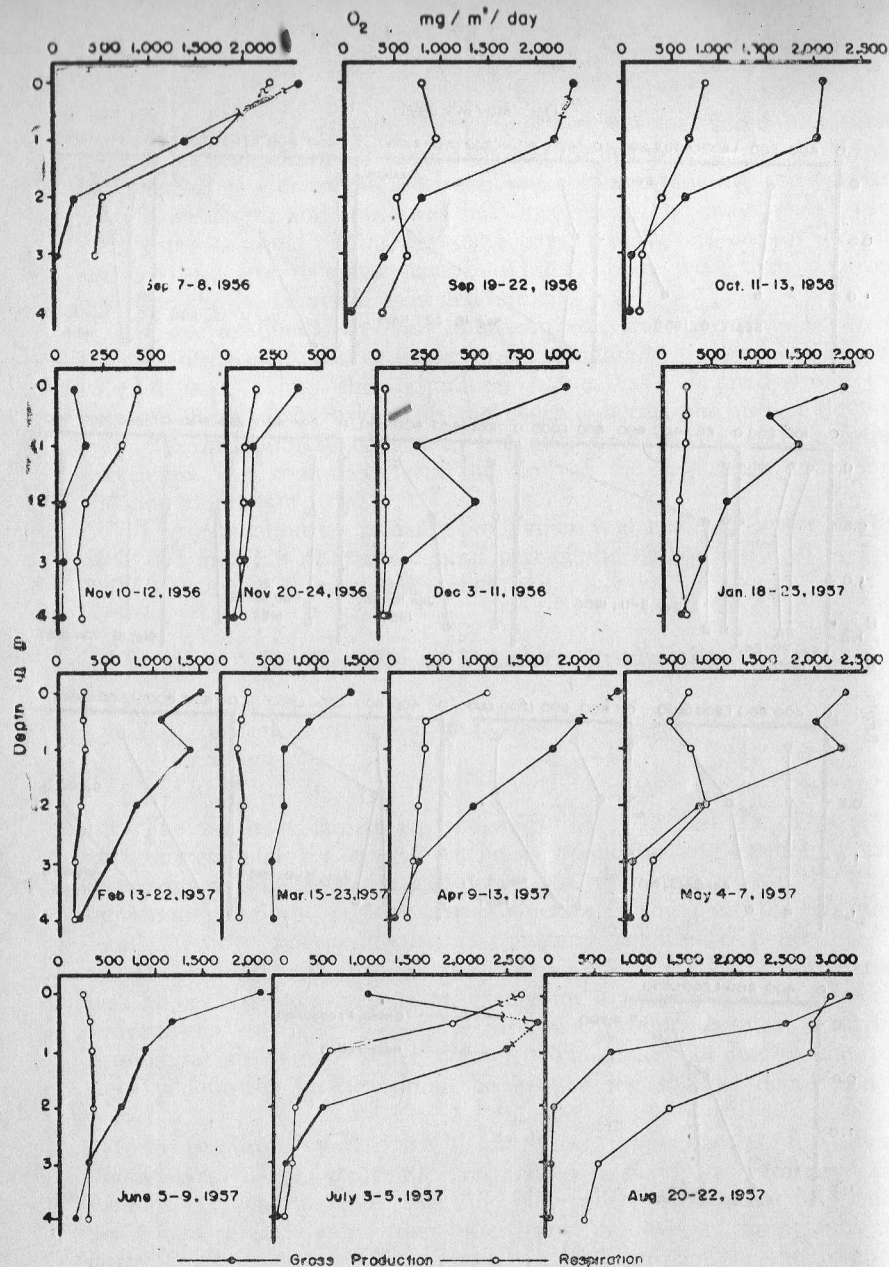


Fig. 23 — Monthly gross production and respiration at every depth of the inner part of the harbor
 Produção bruta mensal e respiração em cada profundidade da parte interior do porto
 Valeur mensuelle de la production brute et de la respiration à toutes les profondeurs dans la partie intérieure du port

of light into the sea water. The respiration of plankton may be affected by the water temperature, but not by the light condition.

Gross production in this area decreased from the surface downward. Vertically, respiration showed only small differences with a few exceptions, in when high respiration had been occurred at the surface water due to reproduction of large numbers of phytoplankton. The effect of the strong light intensity upon the restriction of photosynthesis in surface layer, has been reported by several workers. (Manning and Juday 1941, Hogetsu 1952, and Harvey 1955). Harvey (1955) found that at intensities greater than 0.16 g. cal. per cm^2 . per min. rearrangement or contraction of the chloroplasts in the cells took place. Hogetsu (1952) observed that the maximum activity of the photosynthesis existed slightly below the surface, where the light intensity corresponded approximately to 50 to 70% of the surface intensity, and the light intensity at the compensation point was only about 3 to 5%. In this investigation, it may be due to the restriction of strong light intensity at the surface that the maximum production in summer (July 1957) was obtained at 0.5 meters below the surface.

Fig. 24 and 25 show the monthly variation of the production in each layer. At St. III, the gross production showed generally higher values than respiration, at St. V, on the other hand, the gross production in the layer above 2 meters was usually higher than the respiration, while, below 3 meters the respiration was higher than the gross production. It will be noted that higher respiration in every layer is obtained in the season of high water temperature than in low water temperature, although this is not true for gross production at these stations. The seasonal variation of gross production and the respiration was rather high in the upper layers and low in the deeper layers.

2. Production in water column (1m^2)

On the basis of the above results, the monthly variation of the daily oxygen production throughout the water column per unit area (m^2) is shown in Table 14 and 15, and Fig. 26.

The oxygen production at St. V was much higher than at St. III, although there was a minimum value in November and a maximum value in July at both stations. There was low oxygen production between November and March and high oxygen production between April and October at St. III. On the other hand, at St. V, high values were obtained in June, July and September with value of more than $5,000\text{mg}/\text{m}^2/\text{day}$, and values of less than $1,500\text{mg}/\text{m}^2/\text{day}$ in November and December. As a whole, it may be concluded that the oxygen production is high in the summer and low in the winter.

The annual variations of oxygen production are as follows, and the parenthesized numbers show average value.

O_2 mg/m²/day

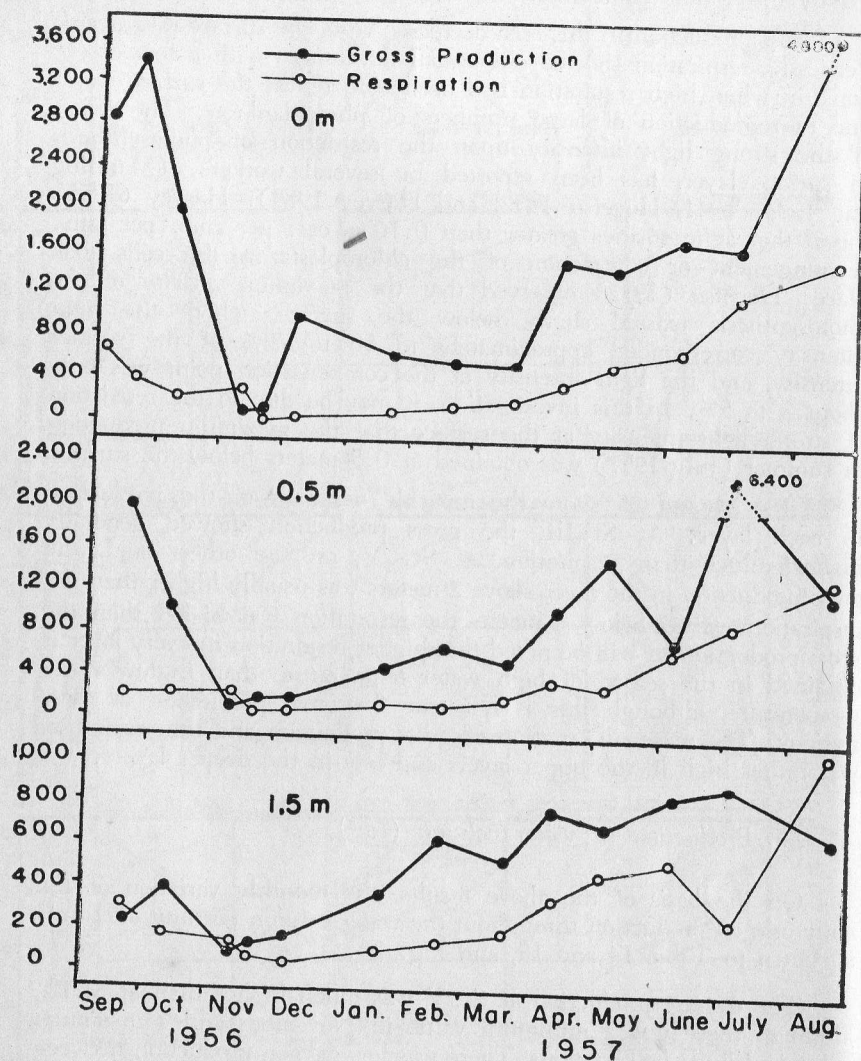


Fig. 24 — Seasonal variation of gross production and respiration at every depth of central part of the harbor

Variação estacional da produção bruta e respiração em cada profundidade da parte central do porto.

Variation saisonnière de la production brute et de la respiration à toutes les profondeurs de la partie centrale du port

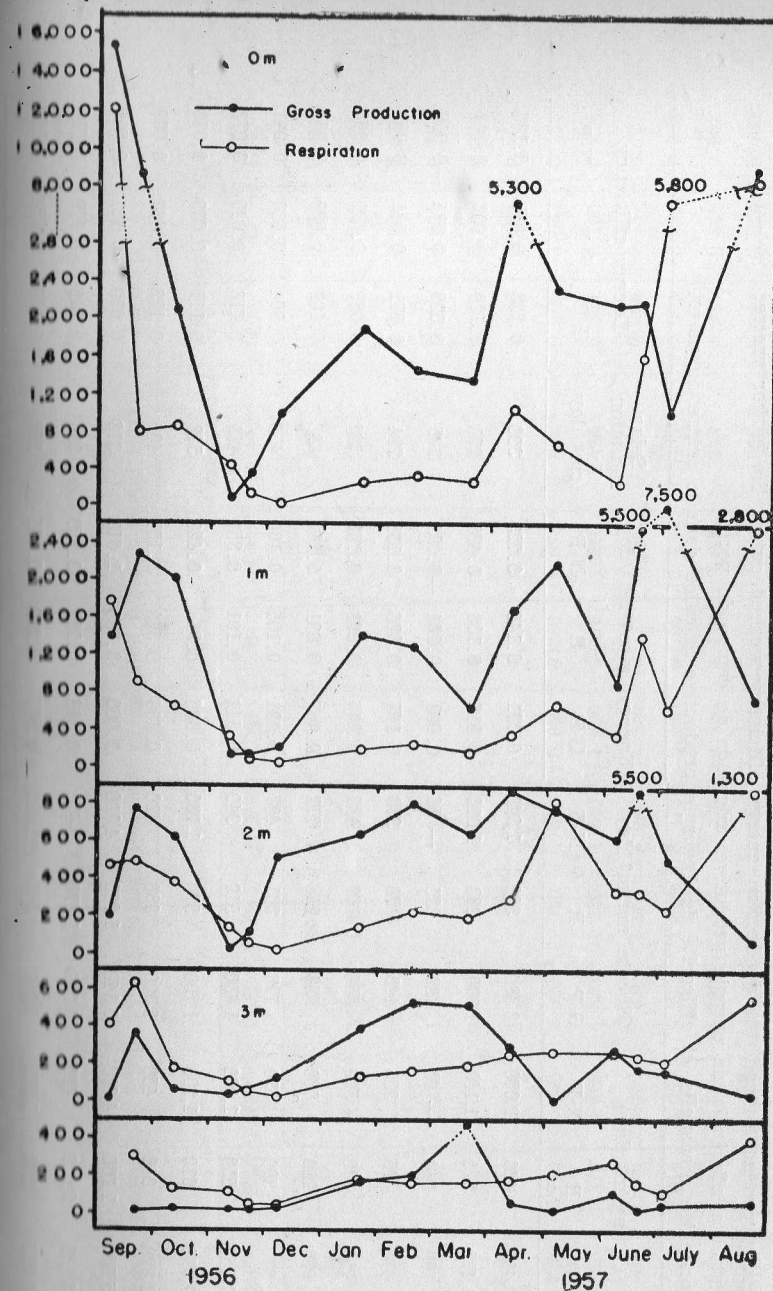


Fig. 25 — Seasonal variation of gross production and respiration at every depth of inner part of the harbor

Variação estacional da produção bruta e respiração em cada profundidade da parte interior do porto.

Variation saisonnière de la production brute et de la respiration à toutes les profondeurs dans la partie intérieure du port

T A B L E 14

Monthly primary production and the productive energy efficiency worked out at the harbor centre.

Produção mensal e eficiência de energia produtiva calculada no centro do porto.

Production primaire mensuelle et efficacité de l'énergie productive calculée dans le centre du port.

| Month | O ₂ mg/m ² /day | | | Glucose mg/m ² /day | | | Energy g-cal/cm ² /day | | | Solar radiation g-cal/cm ² /day | Energy efficiency | | |
|------------|---------------------------------------|-------|-------|--------------------------------|-------|-------|-----------------------------------|-------|--------|--|-------------------|-------|--------|
| | G-P | R | N-P | G-P | R | N-P | G-P | R | N-P | | G-P | R | N-P |
| Sep., 1956 | 2,490 | 420 | 2,070 | 2,330 | 390 | 1,940 | 0.871 | 0.146 | 0.725 | 390 | 0.223 | 0.037 | 0.186 |
| Oct., | 1,470 | 310 | 1,160 | 1,380 | 290 | 1,090 | 0.516 | 0.108 | 0.408 | 288 | 0.179 | 0.038 | 0.142 |
| Nov., | 180 | 240 | — 60 | 169 | 225 | — 56 | 0.063 | 0.084 | —0.021 | 245 | 0.026 | 0.034 | —0.009 |
| Dec., | 470 | 75 | 395 | 440 | 70 | 370 | 0.165 | 0.026 | 0.138 | 234 | 0.071 | 0.011 | 0.059 |
| Jan., 1957 | 700 | 180 | 520 | 656 | 169 | 487 | 0.245 | 0.063 | 0.182 | 282 | 0.087 | 0.022 | 0.065 |
| Feb., | 990 | 230 | 760 | 928 | 216 | 712 | 0.347 | 0.081 | 0.266 | 318 | 0.109 | 0.025 | 0.084 |
| Mar., | 830 | 300 | 530 | 778 | 281 | 497 | 0.291 | 0.105 | 0.186 | 452 | 0.064 | 0.023 | 0.041 |
| Apr., | 1,550 | 550 | 1,000 | 1,450 | 510 | 940 | 0.542 | 0.191 | 0.352 | 479 | 0.113 | 0.040 | 0.073 |
| May., | 1,810 | 610 | 1,200 | 1,700 | 570 | 1,130 | 0.636 | 0.213 | 0.423 | 542 | 0.117 | 0.039 | 0.078 |
| June, | 1,390 | 940 | 450 | 1,300 | 880 | 420 | 0.486 | 0.329 | 0.157 | 400 | 0.122 | 0.082 | 0.039 |
| July, | 5,700 | 1,100 | 4,600 | 5,340 | 1,030 | 4,310 | 2.000 | 0.385 | 1.610 | 318 | 0.629 | 0.121 | 0.506 |
| Aug., | 2,440 | 2,010 | 430 | 2,290 | 1,890 | 400 | 0.856 | 0.707 | 0.150 | 396 | 0.216 | 0.179 | 0.038 |
| Average | 1,670 | 580 | 1,090 | 1,560 | 540 | 1,020 | 0.585 | 0.203 | 0.381 | 362 | 0.163 | 0.054 | 0.109 |

T A B L E 15

Monthly primary production and the productive energy efficiency worked out at the inner part of the harbor.

Produção primária mensal e eficiência de energia produtiva calculada no interior do porto.

Production primaire mensuelle et efficacité de l'énergie productive calculée dans la partie intérieure du port.

| Month | O ₂ mg/m ² /day | | | Glucose mg/m ² /day | | | Energy g-cal/cm ² /day | | | Solar radiation g-cal/cm ² /day | Energy efficiency | | |
|-----------|---------------------------------------|-------|--------|--------------------------------|-------|--------|-----------------------------------|--------|--------|--|-------------------|-------|--------|
| | G-P | R | N-P | G-P | R | N-P | G-P | R | N-P | | G-P | R | N-P |
| Sep. 1956 | 7.790 | 2.640 | 5.150 | 7.300 | 2.480 | 4.820 | 2.730 | 0.928 | 1.800 | 390 | 0.700 | 0.238 | 0.462 |
| Oct., | 3.820 | 1.730 | 2.090 | 3.580 | 1.620 | 1.960 | 1.340 | 0.606 | 0.733 | 288 | 0.462 | 0.210 | 0.255 |
| Nov., | 390 | 590 | —200 | 370 | 550 | — 180 | 0.138 | 0.206 | —0.068 | 245 | 0.056 | 0.084 | —0.028 |
| Dec., | 1.370 | 140 | 1.230 | 1.280 | 130 | 1.150 | 0.479 | 0.049 | 0.430 | 234 | 0.205 | 0.021 | 0.184 |
| Jan, 1957 | 3.900 | 810 | 3.090 | 3.660 | 760 | 2.900 | 1.370 | 0.284 | 1.090 | 282 | 0.486 | 0.101 | 0.387 |
| Feb., | 3.580 | 840 | 2.740 | 3.360 | 790 | 2.570 | 1.260 | 0.295 | 0.961 | 318 | 0.396 | 0.093 | 0.302 |
| Mar., | 2.730 | 770 | 1.960 | 2.560 | 720 | 1.840 | 0.957 | 0.269 | 0.688 | 452 | 0.212 | 0.060 | 0.152 |
| Apr., | 4.820 | 1.370 | 3.450 | 4.520 | 1.280 | 3.240 | 1.690 | 0.479 | 1.210 | 479 | 0.353 | 0.100 | 0.253 |
| May., | 4.090 | 2.110 | 1.980 | 3.830 | 1.980 | 1.850 | 1.430 | 0.741 | 0.690 | 542 | 0.264 | 0.137 | 0.127 |
| June, | 6.070 | 2.010 | 4.060 | 5.690 | 1.880 | 3.810 | 2.130 | 0.700 | 1.430 | 400 | 0.533 | 0.175 | 0.358 |
| July, | 12.050 | 3.340 | 8.710 | 11.300 | 3.130 | 8.170 | 4.230 | 1.170 | 3.060 | 318 | 1.330 | 0.368 | 0.962 |
| Aug, | 4.510 | 9.690 | —5.180 | 4.230 | 9.080 | —4.850 | 1.580 | —3.400 | —1.820 | 396 | 0.399 | 0.859 | —0.460 |
| Average | 4.590 | 2.170 | 2.420 | 4.300 | 2.030 | 2.270 | 1.610 | 0.761 | 0.850 | | 0.450 | 0.204 | 0.246 |

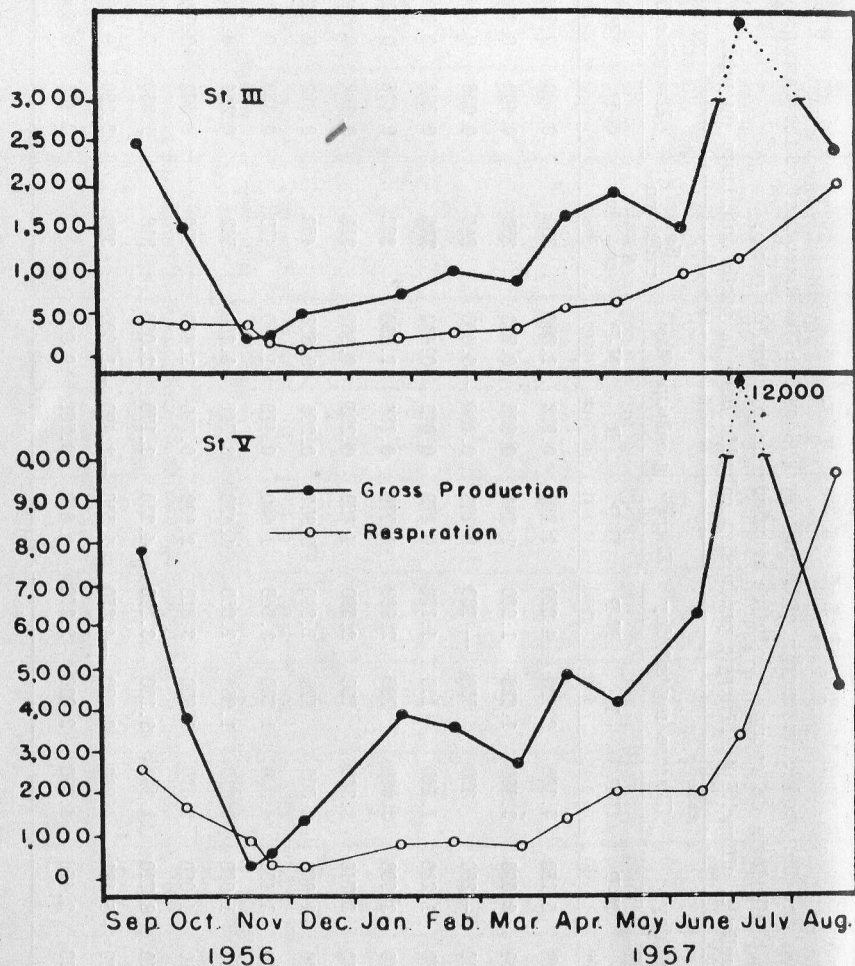
O₂ mg/m²/day

Fig. 26 -- Seasonal variation of gross production and respiration in water column (m²)
 Variação estacional da produção bruta e respiração na coluna de água (m²)
 Valeur mensuelle de la production brute et de la respiration dans une colonne d'eau (m²)

St. III

St. V

Gross

production 180—5,700 (1,670)mg.O₂/m²/day 390—12,050 (4,590)mg.O₂/m²/day

Net

production -60—4,600 (1,090) " -5,180—8,710 (2,420) "

Respiration

75—2,010 (580) " 140—9,690 (2,170) "

The oxygen production at St.V was very high when compared with that at St.III. The high oxygen production at St.V may be related to the abundant supply of plant nutrients flowing into this area in city sewage water.

The relation between the gross production and the respiration, about 1/3 to 1/2, agrees with the results obtained by Hogetsu (1952) in the lak of Suwa.

From the many estimates of the primary organic production in various sea areas by C₁₄ method, Steemann Nielsen (1953) reported the following values, 500 — 3,000 mg.C/m²/ day in the high production area, 50 mg.C/m²/day in the low production area, and 150 mg.C/m²/day as the average through whole ocean. Riley (1953) reported that the production in the ocean was 300—1,500 mg.C/m²/day, using the O₂ method.

Regarding production in lakes, Hogetsu (1952) reported 800 mg.C/m²/day on average in the lake of Suwa, and Saijo (1956) obtained values ranging 120 to 210 mg.C/m²/day during summer in the Kizaki, Nakazuna and Aoki-lakes.

Ryther (1954) has suggested that a photosynthetic quotient (O₂/CO₂) of 1.25 is perhaps more realistic than that of unity. Accordingly, to compare the author's value in Shiogama Habor with the other values, the above oxygen production was calculated in carbon using a photosynthetic quotient of 1.25.

The production at St.V is probably unusual under natural conditions because of its location at the inner part of Shiogama Habor. The calculated production shows values ranging from 54 to 1,710 mg.C/m²/day, (504 mg.C/m²/day, on the average) at St. III, and from 117 to 3,600 mg.C/m²/day (1,380 mg.C/m²/day on the average) at St. V. The results at St. III compare favorably Riley's and Steemann Nielsen's values in the high production area. Annual production in both stations are summerized as follows:

| | St. III | St. V |
|------------------|------------------------------|------------------------------|
| Gross production | 180 g.c/m ² /year | 500 g.c/m ² /year |
| Net production | 60 " | 240 " |
| Respiration | 120 " | 260 " |

If St. III is representative of the average in Matsushima Bay, the

annual production in Matsushima Bay comes up to 9,200, 3,200 and 6,000 tons C/year annually for the gross production the respiration and the net production respectively.

C. Relation between the Compensation Point and Transparency

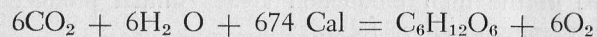
The relation between the light intensity at the compensation point and at the depth of transparency, has been reported by many workers. Hogetsu (1952) has indicated that the light intensity at the compensation point corresponds to 3 or 4% of that at the surface. Estimates of the percent of the light intensity at the depth of transparency compared to that at the surface have been reported as follows: 9.9 to 22.6% by Pool and Atkins (1929), 8 to 29% by Clark (1941), 14.5% by Yoshimura (1937), 12-20% by Hogetsu etc. (1952), and 15-16% on the average by Hanaoka and Murakami (1954).

It was reported by Yoshimura (1931) that the compensation depth of the green algae corresponds to 1.25 times the transparency depth, while Clark (1941) estimated it to be 2-2.8 and Hogetsu et al, about two times. On the other hand, Hanaoka and Murakami (1954) suggested that because the intensity of illumination at the transparency depth and the compensation depth may vary with qualitative difference of the suspended materials, it is meaningless to make indiscriminative comparisons between the two.

Table 16 show the compensation depth and transparency depth in the area investigated. These results show that the compensation depth corresponds to 1.4 to 3.1 times (2.4 times on average) the depth of transparency. There is much variation in the relation between the two, although their average agreed fairly well with values given by Clark and Hogetsu. This will be attributable to quantitative variation of the suspended materials.

D. Productive Efficiency of Phytoplankton for Solar Radiation Energy

The phytoplankton obtains carbon for carbohydrate synthesis from the CO_2 in the water according to the equation.



From this equation, the oxygen production or the glucose may be expressed in terms of energy.

The efficiency of production, that is, the fraction of the energy penetrating the sea surface and used in photosynthetic activity, was calculated from the phytoplankton production and data on solar radiation energy from the Sendai Meteorological Station.

The percent efficiency of energy production have been calculated

TABLE 16

Quantitative relation between the compensation depth and transparency of water.

Relação quantitativa entre profundidade de compensação e transparência da água.

Relation quantitative entre la profondeur de compensation et la transparence de l'eau.

| Month | Compensation depth in m. | Transparency in m. | Comp./Transp. |
|------------|--------------------------|--------------------|---------------|
| Sep., 1956 | 1.4 | 0.55 | 2.5 |
| Sep., " | 2.5 | 1.00 | 2.5 |
| Oct., " | 2.7 | 1.30 | 2.1 |
| Nov., " | 3.2 | 2.30 | 1.4 |
| Dec., " | 4.0 | 2.90 | 1.4 |
| Jan., 1957 | 4.0 | 1.70 | 2.4 |
| Feb., " | 4.0 | 1.50 | 2.7 |
| Apr., " | 3.3 | 1.10 | 3.0 |
| May, " | 2.0 | 0.80 | 2.5 |
| June, " | 3.0 | 1.20 | 2.5 |
| July, " | 2.8 | 0.90 | 3.1 |

by several workers, as follows: In the lake, 0.336% in gross production and 0.25% in net production by Juday (1940), 0.1-0.4% in gross production by Lindman (1942), 0.22% in gross production and 0.15% in net production by Hogetsu et al (1952), and 0.02 - 0.05% in gross production during the summer by Saijo (1956). In the sea, the efficiency of gross production was given as 0.55 - 0.82% by Riley (1941), 0.3% by Clark (1946) and 0.1% on the basis of indirect results by Hanaoka (1952).

The energy efficiencies in this area are shown in Table 14 and 15. There was a great difference between the two stations. The efficiency of gross production, was 0.029 to 0.63% (0.16% on annual average) at St. III, and 0.056 to 1.3% (0.45% on annual average) at St. V. Furthermore, the efficiency of the net production averaged 0.11% at St. III and 0.25% at St. V.

E. Standing Crop of Net Plankton

The collection of the plankton in Shiogama Harbor (near St. V)

was made vertically from the surface to the bottom using a quantitative plankton net. The total-N and the total-P in the plankton samples were estimated after the filtration through filter-paper. Table 17 shows the standing crop of net plankton expressed in

TABLE 17

Monthly standing crop of net plankton, showed in terms of nitrogen and phosphorus.

Teor mensal de plancton em função do nitrogênio e fósforo.

Teneur mensuelle de la collecte de plancton exprimée en azote et phosphore.

| Month | Total-N mg/m ³ | Total-P mg/m ³ | N/P |
|------------|---------------------------|---------------------------|------|
| Jan., 1956 | 4.4 | 0.63 | 7.0 |
| Feb. " | 4.6 | 0.72 | 6.4 |
| Mar. " | 6.8 | 0.78 | 8.7 |
| Apr. " | 13.0 | 1.4 | 9.3 |
| May " | 4.4 | 0.88 | 5.0 |
| June " | 6.0 | 1.0 | 6.0 |
| July " | 4.9 | 0.77 | 6.4 |
| Aug. " | 6.7 | 0.90 | 7.4 |
| Sep. " | 14.7 | 1.3 | 11.0 |
| Oct. " | 3.3 | 0.68 | 4.9 |
| Nov. " | 2.4 | 0.60 | 4.0 |
| Dec. " | 1.5 | 0.35 | 4.3 |
| Average | 6.1 | 0.83 | 6.7 |

terms of total-N and in total-P.

The highest values were obtained in April and September, and lowest values in November and December.

As a whole, the range in variations was 1.5 to 15 mg/m³ (6.1 mg/m³ average) in total-N, 0.35 to 1.4 mg/m³ (0.83 mg/m³ average) for total-P, and 4.0 to 11 (6.7 average) in the ratio of nitrogen to phosphorus.

Summary

Observations were made on the phytoplankton production and

the standing crop of net plankton. The results may be summarized briefly as follows:

a. Phytoplankton production

(1) There was a general tendency to be high values during the summer and low values during the winter in gross production and respiration. The annual average of gross production was 504 mg/m²/day at St. III and 1,380 mg/m²/day at St. V. (These values are expressed in carbon).

(2) The most common compensation depth in this area was found to be approximately 2 to 3 meters.

(3) The compensation depth corresponded to from 1.4 to 3.1 times (average 2.4 times) the depth of transparency.

(4) The energy efficiency of production showed the values ranging from 0.029 to 0.63% with 0.16% on the average at St III, and 0.05 to 1.3% with 0.45% on the average at St V. The average efficiency of net production was 0.11% at St. III and 0.25% at St. V.

b. Standing crop of net plankton

Highest values were found in April and October and lowest values in November and December. The average of standing crop of plankton was 6.1 mg/m³ in total-N, 0.83 mg/m³ in total-P, and 6.7 in the N/P ratio.

VI. MATERIALS SUSPENDED IN THE BAY

Materials suspended in the sea play an important rôle in the metabolic circulation of nutrients. The materials suspended in the shallow bay may be composed of not only planktonic aggregates but also of materials refloated from the bottom as well as terrestrial materials such as inorganic debris and epidermis fragments of land plants.

There is considerable literatures on utilization of materials suspended by animals for feed. Fox (1950) reported that shell fish and other aquatic animals ingest the materials suspended in the sea water for food. Furthermore, Hanoaka (1953) has expressed the same view from the results of his experiments and from those of many other investigator's.

The fresh sediments on the bottom, just after being deposited, contain much easily decomposable organic matter. This may be decomposed by bacteria or chemically, or be grazed by the animals. As a consequence, some parts of the organic material in the fresh sediments may return into the overlying water and others may remain in place.

Accordingly, the materials suspended in the sea may play an important rôle in the circulation of nutrients by the various processes mentioned above.

With this in mind, observations were made on materials suspended in Matsushima Bay, the results of which are described below.

A. Method of Collecting Materials Suspended

The observations on the materials suspended were made near at St. III (Fig. 6). At the observation point the water is 1.5 — 3.0m deep depending on the tide. It is in the cultural ground of laver.

Eight glass tubes about 3cm in diameter were fixed in a wooden frame, and then suspended at a depth of 20 cm above the bottom. At intervals of 1 to 28 days (mostly 3 to 7 days), they were raised and their contents were examined as follows, one was used for biological observation, and the others for the estimation of the amount of material suspended and for chemical analysis after drying.

In order to obtain an information on the materials suspended and their chemical and biological nature, the author made the following observations in the Shiogama Harbor from April 1956 to January 1958.

The observations on vertical variation of materials suspended were made at the inner part of the harbor in water 4-5m deep.

The glass tubes were hung in four groups at intervals of one meter from the surface of the water.

B. Vertical Distribution of Materials Suspended and of Their Biological and Chemical Composition

The amounts of materials deposited in the tubes vary in proportion to the density of materials suspended in the sea water just over the mouth of tube.

1. Amount of material suspended

As will be seen from Table 18, the amounts of materials suspended were least in the upper most layer and highest in the deepest layer, and increased vertically from the upper layer to the deepest layer. Those in April and September showed considerably higher values than those in February and October, especially those in April were greatly different from the others. It will be noticeable that the ratio of the amount of deposits in the upper layer to that in the deepest layer ranged from 1/2.2 to 1/2.8.

2. Organisms in material suspended

Both the numbers of species and individual organisms were found in greater abundance at the top layer (1m under the sea level). The number of species found in October was greater than in the other months. The dominant species numeracally were as follows; *Skeletonema* sp. in September, *Navicula* sp. in October, *Skeletonema* sp., *Thalassiosira* sp. and *Eucampia* sp. in February, and *Pleurosigma*

TABLE 18

Vertical distribution of suspended material, and P.N.C. N/P and C/N.
Distribuição vertical do material em suspensão e P, N, C, N/P e C/N.
Distribution verticale du matériel en suspension P, N, C, N/P et C/N.

| Date | Depth of Water in m. | Dry Weight of Deposits g/m ² day | Total—P% | Total—N% | Organic—C % | N/P | C/N |
|-------------------|----------------------|---|----------|----------|-------------|-----|------|
| Sep. 4 — 14 1956 | 1 | 49 | 0.110 | 0.827 | 6.68 | 7.5 | 8.1 |
| | 2 | 78 | 0.092 | 0.621 | 6.43 | 6.8 | 10.4 |
| | 3 | 95 | 0.086 | 0.549 | 6.13 | 6.4 | 11.2 |
| | 4 | 110 | 0.085 | 0.455 | 5.16 | 5.4 | 11.3 |
| Oct. 10 — 20 1956 | 1 | 36 | 0.120 | 0.554 | 5.23 | 4.6 | 9.4 |
| | 2 | 45 | 0.100 | 0.393 | 4.25 | 3.9 | 10.8 |
| | 3 | 58 | 0.094 | 0.359 | 4.08 | 3.8 | 11.4 |
| | 4 | 83 | 0.093 | 0.336 | 4.04 | 3.6 | 12.0 |
| Feb. 15 — 22 1957 | 1 | 21 | 0.087 | 0.516 | 5.36 | 5.9 | 10.4 |
| | 2 | 24 | 0.087 | 0.467 | 4.99 | 5.4 | 10.7 |
| | 3 | 36 | 0.100 | 0.469 | 5.14 | 4.7 | 11.0 |
| | 4 | 58 | 0.102 | 0.472 | 5.12 | 4.6 | 10.8 |
| Apr. 24 — 30 1957 | 1 | 110 | 0.080 | 0.356 | 4.98 | 4.5 | 14.0 |
| | 2 | 205 | 0.062 | 0.294 | 4.41 | 4.7 | 15.0 |
| | 3 | 215 | 0.063 | 0.297 | 4.52 | 4.7 | 15.2 |
| | 4 | 300 | 0.064 | 0.304 | 4.35 | 4.8 | 14.3 |

sp. and *Coconeis* sp. in April. The total individual numbers varied a maximum in October to a minimum in April.

3. Total—P, total—N and organic—C in the material suspended

Total—N and organic—C values showed highest and had a tendency to decrease from the upper layer to the deepest. Although the ratio of N to P in April was nearly similar vertically, in other months it decreased vertically from the upper layer to the deeper layer. The ratio of C to N did not follow this pattern. In September and October it showed a tendency to decrease from the upper layer to the deeper layer, in February there was little difference vertically, and in April the ratio of the middle layer was higher than that of other layer. The total—N and organic—C in September showed a higher value than those in other months. In April three elements were lower than in the other months. However, it should be noted that the contents of these elements were generally higher in these material suspended than in the surface layer bottom sediments.

Then, chemical composition of the material suspended may depend on the rate of mixing of organic materials from plankton and from

materials refloated from the bottom. The organic content in the latter is very low in comparison with that in the former. As the materials refloated from the bottom may be more concentrated near the bottom than near surface, the contents of total-P, total-N and organic-C in the deepest layer may be lower than those in the upper layers.

The higher amount of material suspended and lower content of organic materials in April may be due to more materials refloated from the bottom because of strong south-east winds. Furthermore, the reason for the lower content of organic matter (indicated by the content of total-P, total-N and organic-C) in the deeper layer may be caused not only by the factors mentioned above, but also by decomposition of organic matter during the sinking of the materials suspended to the bottom.

C. Seasonal Variations of Materials Suspended and of Their Chemical Composition

1. Relation between seasonal variations of material suspended and meteorological and oceanographical conditions.

Although four unusual materials suspended ranging from 660 to 2.040 g/m²/day were observed during the period of observation, they were probably due to the refloating of bottom mud because of very strong south-east winds.

The material suspended through the two years actually varied as follows; since the starting of this observation, the high amounts of material suspended lasted until the beginning of October, although these values had a large fluctuation, after which these gradually diminished to minimum during the period from the end of November to the middle of January, the following year.

The deposition period lasted until the middle of April, then, as in the previous year, a heavy deposition followed, which continued until middle of December. It should be noted that the amount of deposition after October 1957 did not decline as much as the previous year, although it declined slightly from the beginning of October. It is also notable that the low deposition in summer was proceeded and was followed by high deposition both years.

From these results, it is evident that the annual variation in material suspended in this area has two maxima, one in spring and another one in autumn, with a minimum in winter and a moderate deposition in summer.

In order to clarify the relation between the variations of the amount of material suspended and the meteorological conditions, the meteorological data are shown in Table 19 and Fig. 27.

There was no agreement between variations in material suspended and the maximum wind velocity or the maximum of daily wind velocity, although these wind velocities varied considerably.

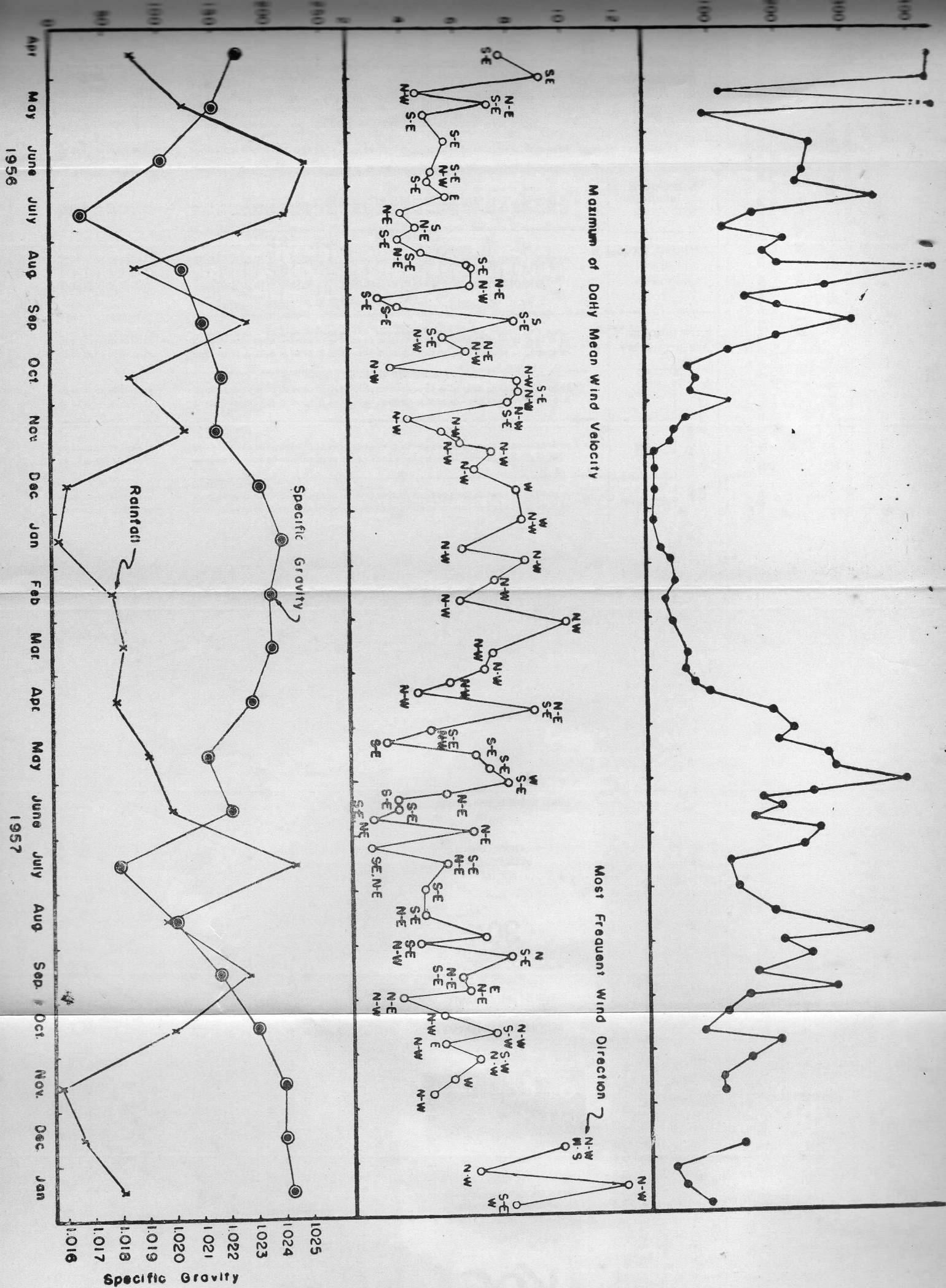


Fig. 27 — Seasonal variation of suspended material and of meteorological conditions

Variação estacional da material em suspensão com as condições meteorológicas

Variation saisonnière du material en suspension et das condi-

Judging from the topographical condition of Matsushima Bay, the refloatation of sediments by wind and waves may be effected by the wind between south-west and north-east rather than the other direction. On the other hand, these Table 19 and Fig. 27 show "most frequent

T A B L E 1 9

Seasonal variation of suspended material and wind velocity.

Variacões estacionais da material em suspensão e da velocidade do vento.

Variations saisonnières du materiel en suspension et de la vitesse du vent.

| Date | Days | Suspended material * g/m ² /day | Most frequent wind direction | Maximum wind velocity/m/sec | Daily mean wind velocity m/sec | | | |
|-------|-------|---|------------------------------|-----------------------------|--------------------------------|------|---------|-----|
| | | | | | Max. | Min. | Average | |
| 1956 | | | | | | | | |
| 4 13 | 4.19 | 6 | 870 | S-E | 12.5 | 7.7 | 3.1 | 4.9 |
| 4 19 | 5.7 | 18 | 660 | S-E | 15.8 | 9.2 | 2.5 | 5.4 |
| 5 7 | 5.9 | 2 | 117 | N-W | 8.9 | 4.5 | 2.5 | 3.7 |
| 5 9 | 5.17 | 8 | 1,060 | N-E,S-E | 16.3 | 7.3 | 1.9 | 3.9 |
| 5 17 | 5.21 | 4 | 91 | S-E | 9.1 | 4.7 | 3.3 | 4.0 |
| 5 19 | 6.18 | 28 | 249 | S-E | 11.3 | 5.7 | 1.3 | 3.3 |
| 5 21 | 6.22 | 4 | 237 | N-W,S-E | 8.4 | 5.2 | 2.0 | 3.3 |
| 5 22 | 6.30 | 8 | 230 | S-E | 10.8 | 4.9 | 1.9 | 3.6 |
| 5 30 | 7.9 | 9 | 348 | E | 8.5 | 5.7 | 1.8 | 3.1 |
| 6 9 | 7.16 | 7 | 165 | N-E | 5.4 | 3.9 | 2.1 | 2.7 |
| 6 16 | 7.25 | 9 | 120 | N-E,S | 6.9 | 4.6 | 1.9 | 2.9 |
| 6 25 | 8.2 | 8 | 213 | S-E | 6.7 | 3.8 | 2.4 | 2.8 |
| 6 3 | 8.9 | 7 | 178 | S-E,N-E | 11.5 | 4.7 | 1.7 | 3.3 |
| 6 9 | 8.17 | 8 | 200 | S-E | 12.4 | 6.5 | 2.1 | 3.1 |
| 6 17 | 8.18 | 1 | 2,040 | S-E | 14.4 | 6.6 | 6.5 | 6.6 |
| 6 18 | 8.30 | 12 | 274 | N-E,N-W | 14.4 | 6.6 | 1.3 | 3.2 |
| 6 30 | 9.4 | 5 | 155 | S-E | 7.1 | 3.1 | 2.1 | 2.5 |
| 6 4 | 9.8 | 4 | 198 | S-E | 8.7 | 3.8 | 2.1 | 3.1 |
| 6 9 | 9.19 | 11 | 317 | S,S-E | 13.0 | 8.2 | 1.9 | 3.2 |
| 6 19 | 9.26 | 7 | 203 | S-E,N-W | 11.8 | 5.4 | 1.7 | 3.4 |
| 6 26 | 10.8 | 12 | 125 | N-E,N-W | 11.8 | 6.4 | 2.6 | 3.8 |
| 6 9 | 10.13 | 5 | 66 | N-W | 10.7 | 3.5 | 2.3 | 3.1 |
| 6 13 | 10.20 | 7 | 76 | N-W | 11.7 | 8.4 | 2.5 | 3.7 |
| 6 20 | 10.26 | 6 | 68 | N-W,S-E | 11.7 | 8.4 | 1.7 | 3.5 |
| 6 26 | 11.6 | 11 | 135 | N-W,S-E | 12.4 | 8.0 | 1.8 | 3.5 |
| 6 9 | 11.12 | 6 | 62 | N-W | 8.4 | 4.1 | 2.3 | 3.2 |
| 6 12 | 11.20 | 8 | 445 | N-W | 13.9 | 5.5 | 3.4 | 4.5 |
| 6 20 | 11.24 | 4 | 39 | N-W | 13.7 | 6.1 | 2.6 | 4.7 |
| 6 24 | 12.3 | 9 | 16 | N-W | 14.9 | 7.4 | 3.1 | 5.0 |
| 6 3 | 12.11 | 8 | 15 | N-W | 15.8 | 6.6 | 2.9 | 4.4 |
| 6 11 | 12.25 | 14 | 16 | W | 13.9 | 8.3 | 2.4 | 4.9 |
| 1957 | | | | | | | | |
| 12 26 | 1.16 | 22 | 12 | W,N-W | 20.8 | 8.5 | 2.0 | 4.3 |
| 12 16 | 1.25 | 9 | 21 | N-W | 13.5 | 6.1 | 1.7 | 3.8 |
| 12 26 | 2.1 | 7 | 41 | N-W | 14.9 | 8.6 | 1.7 | 5.0 |
| 12 1 | 2.15 | 14 | 47 | N-W | 16.8 | 7.4 | 2.4 | 4.7 |
| 12 16 | 2.22 | 7 | 30 | N-W | 11.2 | 6.1 | 2.9 | 4.2 |
| 12 22 | 3.15 | 21 | 39 | N-W | 17.6 | 10.1 | 2.4 | 5.0 |
| 12 16 | 3.23 | 8 | 62 | N-W | 15.3 | 7.3 | 2.7 | 4.6 |
| 12 22 | 4.4 | 12 | 58 | N-W | 16.3 | 7.0 | 2.2 | 4.5 |

| Date | Days | Suspended material * g/m ² /day | Most frequent wind direction | Maximum wind velocity/m/sec | Daily mean wind velocity m/sec | | |
|---------------|------|---|------------------------------|-----------------------------|--------------------------------|------|---------|
| | | | | | Max. | Min. | Average |
| 4.4 ~ 4.9 | 5 | 73 | N-W | 13.0 | 5.7 | 2.8 | 4.0 |
| 4.9 ~ 4.13 | 4 | 97 | N-W | 13.0 | 4.5 | 1.9 | 3.7 |
| 4.13 ~ 4.27 | 14 | 190 | S-E, N-E | 17.6 | 8.9 | 2.4 | 4.5 |
| 4.27 ~ 5.7 | 10 | 219 | S-E, N-W | 10.5 | 5.0 | 3.1 | 4.1 |
| 5.7 ~ 5.10 | 3 | 196 | S-E | 8.0 | 3.3 | 2.2 | 2.9 |
| 5.10 ~ 5.22 | 12 | 272 | S-E | 14.9 | 6.7 | 2.3 | 4.5 |
| 5.22 ~ 5.28 | 6 | 283 | S-E | 13.5 | 7.2 | 2.3 | 4.1 |
| 5.28 ~ 6.5 | 8 | 390 | S-E, N-W | 13.9 | 7.9 | 3.0 | 4.5 |
| 6.5 ~ 6.9 | 4 | 257 | N-E | 13.9 | 5.5 | 2.0 | 3.4 |
| 6.9 ~ 6.12 | 3 | 176 | S-E | 8.2 | 3.7 | 2.4 | 2.9 |
| 6.12 ~ 6.19 | 7 | 204 | S-E | 8.2 | 3.8 | 2.7 | 3.1 |
| 6.19 ~ 6.22 | 3 | 160 | S-E, N-W | 7.3 | 2.8 | 1.4 | 2.4 |
| 6.22 ~ 7.3 | 11 | 258 | N-E | 11.2 | 6.6 | 1.5 | 3.1 |
| 7.3 ~ 7.5 | 2 | 228 | S-E, N-W | 6.9 | 2.8 | 1.5 | 2.2 |
| 7.5 ~ 7.25 | 20 | 122 | S-E, N-E | 8.9 | 5.6 | 1.9 | 3.3 |
| 7.25 ~ 8.7 | 13 | 137 | S-E | 7.8 | 4.8 | 1.5 | 2.7 |
| 8.7 ~ 8.19 | 12 | 188 | S-E, N-E | 7.4 | 4.7 | 1.7 | 2.8 |
| 8.19 ~ 8.29 | 10 | 335 | S-E | 10.8 | 7.0 | 2.3 | 4.4 |
| 8.29 ~ 8.31 | 2 | 202 | S-E, N-W | 10.3 | 4.5 | 1.7 | 3.1 |
| 8.31 ~ 9.14 | 14 | 243 | S-E, N | 14.4 | 8.0 | 1.6 | 3.2 |
| 9.14 ~ 9.20 | 6 | 158 | N-E, S-E | 16.8 | 6.0 | 2.8 | 3.7 |
| 9.20 ~ 9.27 | 7 | 283 | E, N-E | 11.8 | 6.4 | 2.7 | 4.1 |
| 9.27 ~ 10.1 | 4 | 154 | N-E, N-W | 10.5 | 3.8 | 1.9 | 2.9 |
| 10.1 ~ 10.15 | 14 | 116 | N-W | 18.0 | 5.3 | 1.9 | 3.4 |
| 10.15 ~ 10.22 | 7 | 80 | N-W, S-W | 17.3 | 7.4 | 1.9 | 4.4 |
| 10.22 ~ 10.28 | 6 | 195 | E, N-W | 9.8 | 5.3 | 2.2 | 3.3 |
| 10.28 ~ 11.9 | 12 | 148 | S-W, N-W | 14.0 | 6.8 | 2.3 | 3.4 |
| 11.9 ~ 11.19 | 10 | 108 | W | 15.0 | 5.8 | 2.1 | 3.5 |
| 11.19 ~ 11.25 | 6 | 113 | N-W | 10.1 | 4.9 | 2.7 | 3.6 |
| 12.11 ~ 12.31 | 20 | 140 | W-E, N-W | 26.5 | 9.8 | 2.1 | 3.9 |
| 1958 | | | | | | | |
| 12.31 ~ 1.9 | 9 | 39 | N-W | 12.2 | 6.6 | 2.8 | 4.3 |
| 1.9 ~ 1.21 | 2 | 54 | N-W | 20.1 | 12.2 | 2.2 | 5.0 |
| 1.21 ~ 1.28 | 7 | 91 | S-E, W | 14.9 | 7.9 | 2.0 | 4.6 |

* dry weight.

occurrence" of the wind direction between south-west and north-east during spring and the beginning of autumn, and of the opposite direction during the middle of autumn and the beginning of spring.

During the middle of April and September, there was a striking resemblance between the ups and downs of the amount of material suspended and of the maximal velocity of the inshore wind, although both variations are out of all proportion in quantity. On the other hand, in the period of the offshore wind mostly during October and the middle of April, the variations of the amount of material suspended were independent of the maximum of daily mean wind velocity, that is, the highest material suspended in the other season never occurred with maximum daily mean wind velocities of more than 8m/second.

Accordingly, the results indicate that the variation of the amount of material suspended is affected not only by the wind velocity but even more by the direction of wind. The amount of material suspended after October, 1957 did not decline as in the previous year, even though there was no great differences in the meteorological conditions between these years. This may have been caused by dredging and reclaiming work in the vicinity of Yogasaki.

There was a distinct relation between the seasonal variations of rainfall and the amount of material suspended, although there was found some exceptions. After a big rainfall, the mud may be transported into the sea by the rain water flowing in from the rivers.

2. Organisms contained in materials suspended and their seasonal variations

The dominant species of the numerical population in the community were largely a diatom, furthermore, the most of it was a attaching plankton and there were comparatively few floating species (*Chaetoceros* sp., *Skeletonema* sp.) which are abundant in sea water.

As a whole, the following species were observed frequently *Melosira* sp., *Pleurosigma* sp., *Navicula* sp., *Nitzschia* sp. etc. The largest numbers of organisms were found in May, June, and October respectively, while numbers were low in the other seasons. There was a large difference between the amount of suspended material and the number of organisms in deposits. This indicates that amounts of suspended material are not influenced by precipitation of the organisms.

Seasonal highs for several of the dominant species occurred as follows; *Eucampia* sp. during January and March, *Coconeis* sp. during March and June, *Pleurosigma* sp., *Navicula* sp. and *Nitzschia* sp. in spring and in autumn, *Skeletonema* sp., and *Thalassiosira* sp., in winter and *Licomphora* sp. and *Melosira* sp. in December. The dominant species in the community in May, June and October of when the number was especially high, were mostly the attaching plankton such as *Nitzschia longissima* var *reversa* or *Navicula peregrina* var *kefvingensis*.

3. Seasonal variations of total-P, total-N and organic-C in suspended material

The results of chemical analysis are shown in Table 20. High contents of these elements in suspended material were obtained during October and the middle of April, smaller amounts were found in the summer of 1956.

These high values in winter may be due to the small amount of materials refloated in suspended material, together with slow decom-

at the surface layer was higher than at the deeper layer. On the other hand, both species and individual numbers of the organisms (mostly diatom) contained in material suspended were generally in more abundant in the surface layer.

The results showed that the deposits have two maxima, one in spring and another one in autumn, with a minimum in winter and a moderate deposition in summer. The minimum value in winter was less than 1/10 of the maxima in spring or in autumn.

The deposition may be influenced not only by the wind conditions such as velocity and direction (northeast - southeast), but also by the transportation of land soil after a heavy rainfall. Accordingly, the largest of material suspended usually occurs at the time of a strong inshore wind.

The contents of total-N and organic-C in material suspended were generally higher than in surface sediments, although the content of total-P was little difference between the material suspended and surface sediments.

The contents of these elements during October and the middle of April were higher than at other seasons. The largest number of organisms in material suspended was found in May, June and October. The dominant species numerically were diatoms such as *Melosira* sp., *pleurosigma* sp., *Navicula* sp., and *Nitzschia* sp. There was little relation between seasonal variation of material suspended and the individual of organisms.

VII. METABOLISM OF NUTRITIVE ELEMENTS IN SEDIMENTS

Considerable attention has been paid by many workers to the organic matter in sediments and its decomposition. However, the information is incomplete regarding the metabolic process of nutrients between the sediments and the overlying sea water, so that further studies are needed.

In previous chapter, it was reported that nitrogen, phosphorus and organic carbon in the sediments were somewhat higher than those in other bays. Therefore, the metabolic process of nutritive elements in shallow bay sediments such Matsushima Bay may play an important rôle in the metabolic circulation of nutritive elements in this area. In this section the following problems will be discussed, that is, the liberation of soluble nutrients in consequence of the decomposition of organic matter, the return of soluble nutrients from the sediments into the overlying sea water and the transformation of inorganic nitrogen such as ammonia-N, nitrite-N or nitrate-N at the surface of the bottom.

As parts of the above problems have been reported previously by the author (Okuda 1953, 1955 and 1957), the already-published results will be summarized briefly here.

A. Decomposition of Organic Matter in Sediments and Liberation of Soluble Nutrients

1. Influence of the reaction temperature and time for the liberation of ammonia-N and phosphate-P

The samples used in this study were collected from Shiogama Harbor and were divided into three layers from the surface to a depth of 10cm. as follows: 0-0.5, 0.5-5 or 5-10 cm. The sediments consist of 60% which is made up of particles less than 10 microns, and the sediments of the top layer are rich detritus, namely, residues of plants and animals in the process of decomposition. The sediments of the deeper layers contain organic matter which has already undergone extensive decomposition and is different from that of the upper layer.

The samples were stored in the dark for 40 days at temperatures of 5, 10, 15, 20, 25, and 30°C. The amount of soluble nutrients was determined from the difference in the concentration of nutrients after a given experimental period, and was presented as γ/g on the dry matter basis. (Table 21)

The liberation rate of the two elements shows a tendency to increase in proportion to the increase in storage temperature. The liberation of phosphate-P between 15 to 30°C and of ammonia-N from 20 to 30°C was rapid. There is a great difference in the liberation rate of these two elements during storage of mud from different layers. The amount liberated in the top layer (0 - 0.5 cm) was high in comparison with the other two layers (0.5-5 cm and 5-10 cm).

In the upper two layers (0 - 0.5 cm and 0.5 - 5 cm), a gradual decrease of these two elements occurred after the maximum had reached, while in the deeper muds (5 - 10 cm), very slight liberation of these elements occurred during the storage period, and principally between 20°C and 30°C. The apparent maximum liberation values of ammonia-N and phosphate-P in this experiment were 20% and 17% respectively in the surface layer, 4 to 5% each in 0.5 - 5 cm layer, and 0 to 0.7% in the deepest layer.

2. Relation between liberation of soluble nutrients and depth of sediments

The samples for these experiments were collected monthly from four stations in Matsushima Bay (Fig. 6) between April 1954 and February 1955. The sample cores were divided into six layers from the surface to a depth of 40 cm. The results of these experiments are given in Table 22 and 23.

The soluble nutrient content in the surface layer is less than in the deeper layers. It is notable that the amount of soluble nutrients liberated in the surface layer during storage at 26°C for 10 days are usually more abundant than that in the other layer. As a whole, the amount

TABLE 23

Summary of liberation amount of soluble nutrients during April of 1954 to February of 1955.

Resumo da quantidade de liberação dos nutrientes solúveis de Abril de 1954 e Fevereiro de 1955.

Résumé de la quantité d'éléments nutritifs solubles libérée de avril 1954 à février 1955.

| St. No. | Depth of mud. in cm | | Phosphate—P γ/g | | | Ammonia—N γ/g | | |
|---------|---------------------|-----|------------------------|------|---------|----------------------|------|---------|
| | | | Max. | Min. | Average | Max. | Min. | Average |
| I | 0 | 0.5 | 3.0 | 0.3 | 1.6 | 140 | 22 | 66 |
| | 0.5 | 5 | 1.6 | -2.6 | 0.10 | 68 | 9.8 | 33 |
| | 5 | 10 | 1.0 | -1.2 | -0.17 | 67 | -4.5 | 15 |
| II | 0 | 0.5 | 23 | 0 | 8.0 | 240 | 38 | 119 |
| | 0.5 | 5 | 2.9 | 0 | 0.84 | 120 | 2.2 | 44 |
| | 5 | 10 | 8.5 | -1.2 | 0.81 | 19 | -11 | 7.1 |
| III | 0 | 0.5 | 18 | 1.1 | 6.2 | 350 | 36 | 150 |
| | 0.5 | 5 | 8.7 | -1.5 | 2.3 | 190 | 28 | 92 |
| | 5 | 10 | 3.3 | -0.5 | 0.91 | 64 | -0.9 | 20 |
| V | 0 | 0.5 | 73 | 10 | 34 | 960 | 49 | 340 |
| | 0.5 | 5 | 29 | 2.5 | 11 | 100 | 23 | 176 |
| | 5 | 10 | 10 | -3.0 | 2.6 | 130 | -17 | 24 |

liberated decreases with increasing depth in mud. This is probably because the organic matter in the mud of the deeper layers had considerably decomposed more than that of the upper layer. In general, the amount of soluble nutrients liberated in the surface layer during summer, is higher than during the winter.

3. Influence of bacterial action on liberation of ammonia-N and phosphate-P

Five grams of glucose were added to 150 grams of fresh mud to stimulate bacterial growth. This resulted in a decrease in the amount of soluble nutrients liberated. Apparently, during growth, the bacteria used a considerable amount of the liberation ammonia-N and phosphate-P. (Table 24)

When a toluen-chloroform solution was added to the mud to prevent bacterial growth, ammonia-N and phosphate-P were liberated rapidly for three to five days and then more slowly until the end of the storage period. In the case of the treated mud, there was little difference

TABLE 24

Examination on causes of liberation of soluble nutrients.

Exame das causas de libertação dos nutrientes solúveis.

Examen des causes de libération des éléments nutritifs solubles.

| Treatment | | | No—addition | Glucose added | Toluen and chloroform added |
|------------------------|------|----------------------|---------------------|-----------------------|-----------------------------|
| Ammonia—N γ/g | 6°C | Max. Min. Last value | 450 (61) tr (1) 450 | 68 (61) 1.7 (3.5) 68 | 81 (61) 16 (1) 81 |
| | 26°C | Max. Min. Last value | 980 (61) 78 (1) 980 | 430 (15) 6.4 (1) 8.6 | 100 (10,61) 38 (1) 100 |
| Phosphate—P γ/g | 6°C | Max. Min. Last value | 70 (33) 1 (1) 58 | 0.8 (1) -3.2 (5) -2.8 | 54 (10) 33 (1) 51 |
| | 26°C | Max. Min. Last value | 91 (10) 4 (1) 35 | 77 (15) -5 (1) -0.4 | 47 (24,47) 33 (1) 45 |

rence in the rate of liberation of soluble nutrients between samples stored at 6°C and at 26°C, and the apparent maximum amount of these two elements liberated were small compared with the untreated samples. The slower decomposition of organic matter in mud probably occurred because the bacterial action was restricted due to the addition of the antiseptic.

Matsue (1953) reported that the addition of toluen or chloroform to Diatoms leads to the liberation of phosphate-P stored in their cells. The rapid liberation of ammonia-N and phosphate-P may be the liberation of these stored elements in cells because of the addition of antiseptic as Matsue observed.

The variation of phosphate-P in sediments during storage was in contrast to ammonia-N. In the upper layer of mud, a gradual decrease in phosphate-P occurred after reaching a maximum, while in the deeper mud, phosphate-P continued to decrease through the whole storage period. This is probably caused by the development of bacteria as above mentioned.

4. An experimental formula for decomposition of organic nitrogen in sediments

The work described in this section is an attempt to gain further

information on the decomposition of organic nitrogen in sediments. An experimental formula on the decomposition of organic nitrogen was obtained from the results below.

a. Material and method

In a previous experiment, the concentration of ammonia-N released from sediments during shaking with sea water was determined following incubation at various temperatures. In this method, because the released ammonia-N stays in sediments, part of the released ammonia-N may escape into air and part of it may be used by bacteria during incubation. Accordingly, the actual amount of released ammonia-N may be not determined in this method. To avoid this possibility, the following method was employed in this work. The sample of sediments was obtained from the Shiogama Harbor and it was almost always muddy.

Material was prepared as follows: after gathering surface sediments with spoon, they put through an one mm. sieve, and then mixed well. Fifty grams (raw mud) of the homogeneous sediments were put into a glass tube 7 cm in diameter and 300 ml of the filtered sea water were added. Nine such tubes were allowed to stand for different lengths of time at each temperature, namely, 5, 10, 15, 20, 25, and 30°C. Throughout the experimental period, the supernatant sea water was syphoned off and replaced with fresh sea water of the same temperature every other day. After incubation for 5, 10, 15, 20, 25, 30, 45, 60 or 75 days, the sample from a glass at each temperature was transferred onto filter paper and used for determination of total nitrogen after drying at 105°C. The amount of total nitrogen that remained in the after storage, corresponds to the difference between the initial total nitrogen content and the nitrogen released into the overlying sea water.

b. Rate of decomposition of organic nitrogen

The results are shown in Table 25. The decomposition rate of organic nitrogen was computed as follows. The nitrogen content in the layer below about 10 cm. of the bottom surface shows generally a constant value vertically, although the higher nitrogen content of the sediments is found at the bottom surface and the lower content in the deepest layer. It will be supposed that the constant nitrogen content in the deeper layer corresponds to that under the equilibrium condition at this station. It would be safe to say that the difference between the nitrogen content in upper layer and that in the equilibrium layer will correspond to the amount of decomposable nitrogen. Accordingly, the decomposition rate of organic nitrogen was expressed by the proportion of the amount of decomposed nitrogen to the amount of the decomposable total nitrogen. It may be expressed by the following equation.

T A B L E 25

Relations of decomposition rate of organic nitrogen to reaction time and temperature.

Relações da decomposição de nitrogênio orgânico em função do tempo e da temperatura.

Relations entre le taux de décomposition de l'azote organique, le temps et la température.

| Days | Decomposition rate of nitrogen % | | | | | |
|------|----------------------------------|------|------|------|------|------|
| | 5°C | 10°C | 15°C | 20°C | 25°C | 30°C |
| 5 | 5.0 | 8.9 | 14.2 | 20.8 | 31.5 | 37.7 |
| 10 | 9.1 | 17.4 | 26.5 | 38.0 | 47.9 | 57.7 |
| 15 | 11.5 | 21.9 | 33.1 | 44.2 | 55.0 | 62.7 |
| 20 | 16.2 | 26.5 | 38.5 | 53.1 | 63.1 | 71.5 |
| 25 | 21.9 | 34.4 | 46.9 | 56.9 | 68.9 | 79.6 |
| 30 | 25.8 | 39.4 | 50.8 | 61.5 | 72.3 | 79.6 |
| 45 | 31.2 | 45.4 | 58.1 | 66.9 | 70.0 | 82.3 |
| 60 | 34.6 | 52.7 | 63.1 | 70.0 | 77.3 | 82.7 |
| 75 | 43.1 | 57.7 | 64.2 | 73.1 | 81.9 | 84.6 |

$$Y = \frac{(I-E) - (M-E)}{(I-E)} = \frac{(I-M)}{(I-E)}$$

I — Initial nitrogen content in samples.

M — Determined nitrogen content in samples.

E — Content of nitrogen in the equilibrium layer.

Y — Decomposition rate of nitrogen.

These values were estimated on the dry matter basis as follows: 4,740 mg/g in the initial nitrogen content (I), 2,140 mg/g in the nitrogen content (E) at the equilibrium layer in the sediments and 2,600 mg/g in the decomposable nitrogen in samples (I-E). (Table 26)

As will be seen from Table 26 and Fig. 30, the amount of decomposed nitrogen shows a remarkably regular variation with the increase of storage time at each temperature. The relationship between the decomposition rate of nitrogen, the time and temperature in storage, was obtained as follows;

The relationship between the decomposition rate of nitrogen (Y)

and the reaction temperature (X) is shown in Fig. 28. A nearly linear

T A B L E 2 6

Relations of reaction time to C and K

Relações entre o tempo, C, e K

Relations entre le temps, C et K.

| Days | C | K |
|------|--------|-------|
| 5 | 0.007 | 1.151 |
| 10 | 0.0165 | 1.041 |
| 15 | 0.0238 | 0.974 |
| 20 | 0.0399 | 0.851 |
| 25 | 0.0692 | 0.707 |
| 30 | 0.0923 | 0.634 |
| 45 | 0.132 | 0.539 |
| 60 | 0.167 | 0.479 |
| 75 | 0.235 | 0.380 |

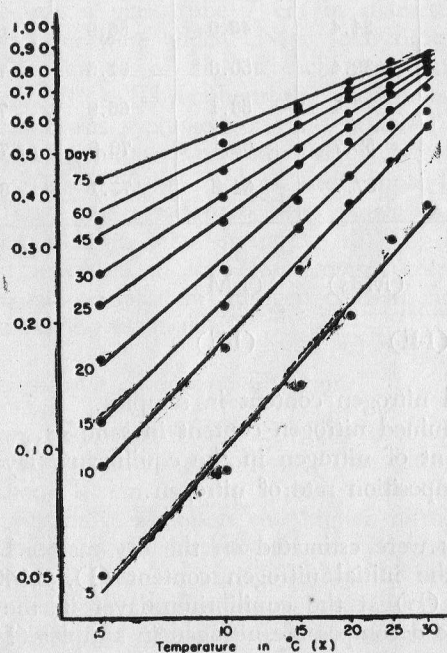


Fig. 28 — Relations between decomposition rate of organic nitrogen and temperature

Relações entre decomposição de nitrogênio orgânico e temperatura

Relation entre la rapport de décomposition de l'azote organique et la température de réaction.

TABLE 17

Vertical distribution of diffused amount of soluble nutrients in mud column at the end of experiment.

Distribuição vertical da quantidade dos nutrientes solúveis difundidos na coluna de lama no fim da experiência.

Repartition verticale des quantités d'éléments nutritifs solubles na diffusés dans une colonne de vase à la fin de l'expérience.

| Depth in mud column | Silicate — Si | | | | Phosphate — P | | | | Total inorganic—N | | | |
|------------------------------|---------------|------|------|----------------------------|---------------|-------|------|----------------------------|-------------------|------|------|----------------------------|
| | I | F | I-F | $\frac{I-F}{I} \times 100$ | I | F | I-F | $\frac{I-F}{I} \times 100$ | I | F | I-F | $\frac{I-F}{I} \times 100$ |
| 0— 0.5 | 2.4 | 0.1 | 2.3 | 95.8 | 0.33 | 0.12 | 0.21 | 63.6 | 2.0 | 0.3 | 1.7 | 85.0 |
| 0.5— 2 | 7.3 | 1.2 | 6.1 | 83.6 | 1.00 | 0.27 | 0.73 | 73.0 | 5.9 | 1.5 | 4.4 | 74.6 |
| 2— 4 | 9.7 | 4.2 | 5.5 | 56.9 | 1.33 | 0.57 | 0.76 | 57.1 | 7.8 | 3.1 | 4.7 | 60.3 |
| 4— 7 | 14.5 | 10.4 | 4.1 | 25.3 | 1.99 | 1.37 | 0.62 | 31.2 | 11.7 | 6.4 | 5.3 | 45.3 |
| 7—10 | 14.5 | 13.3 | 1.2 | 8.3 | 1.99 | 1.63 | 0.36 | 18.1 | 11.7 | 8.6 | 3.1 | 26.5 |
| 10—13 | 14.5 | 14.5 | 1.5 | 0 | 1.99 | 1.87 | 0.12 | 6.0 | 11.7 | 9.4 | 2.3 | 19.7 |
| 13—16 | 14.5 | 14.5 | 1.5 | 0 | 1.99 | 1.87 | 0.12 | 6.0 | 11.7 | 10.2 | 1.5 | 12.8 |
| 16—20 | 19.4 | 19.4 | 2.1 | 0 | 2.66 | 2.50 | 0.16 | 6.0 | 15.7 | 14.6 | 1.1 | 7.0 |
| Total | 96.8 | 77.6 | 19.2 | 19.8 | 13.28 | 10.20 | 3.08 | 23.2 | 78.2 | 54.1 | 24.1 | 30.8 |

I Initial amount of soluble nutrients in mud.

F Final amount of solubles nutrients in mud.

I-F Corresponds to diffused amount of soluble nutrients during experiment.

relationship is found between these two variables. Therefore, the decomposition rate (Y) of organic nitrogen can be calculated by the following equation (The scale of Fig. 28 is logarithms).

$$\log_{10} Y = K \cdot \log_{10} X + \log_{10} C$$

$$Y = C \cdot X^K \dots\dots\dots (1)$$

Table 26 shows the values of (K) and (C), which were computed by the method of least squares. Here, (K) and (C) are a coefficient. Furthermore, there is also a nearly linear relation between these values, (K) and (C) and reaction time as will be seen in Fig. 29. Accordingly this relation is shown by the following equations. That is, the relation between the coefficient, (K), and the reaction time is

$$K = -0.749 \cdot \log_{10} t + 1.780 \text{ ----- (2),}$$

and the relation between the coefficient, (C), and the reaction time is

$$\log_{10} C = 1.340 \cdot \log_{10} t - 3.115$$

$$C = 0.767 \cdot X \cdot 10^{-3} \cdot t^{1.340} \text{ ----- (3).}$$

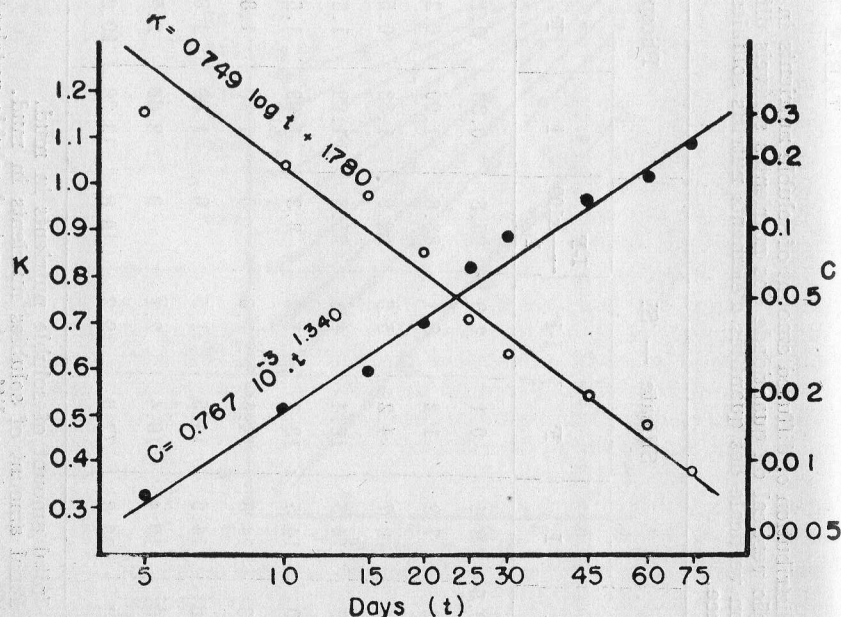


Fig. 29 — Relation of (K) and (C) to reaction period
Relações de (K) e (C) com o período de reação
Relation entre la periode de réaction, (K) et (C)

If the equation (2) and (3) may be substituted for equation (1), we get equation (4) as follows;

$$Y = 0.767 \cdot X \cdot 10^{-3} \cdot t^{1.340} \cdot X^{(-0.749 \cdot \log_{10} t + 1.780)} \text{ ----- (4).}$$

Equation (4) shows the relationship between the decomposition rate of organic nitrogen, the reaction time and the reaction temperature. The calculated values of the decomposition rate of nitrogen from equation (4) are shown in Fig. 30. Fig. 30 indicates the proximity between the observed values and the calculated values for decomposition of organic nitrogen. The decomposition of organic matter in sediments may be somewhat different due to the qualitative difference of organic matter or due to the difference in bacterial activity, therefore, it should be noted that the above experimental equation in no more than an example. In this paper, however, this experimental equation was adapted for estimation of the rate of decomposition of organic nitrogen, as will be described in a later chapter.

B. Return of Soluble Nutrients from Sediments into Overlying Sea Water

1. An experiment on diffusion of soluble nutrients from sediments in to overlying sea water

Fresh mud to a depth of 20 cm was placed in a glass cylinder. Then 700 ml of sea water (containing little soluble nutrients) were added carefully and kept in contact with the mud. The cylinder with its content was allowed to stand in the laboratory away from the direct rays of the sun. The sea water in the cylinder was changed for fresh sea water after one to six days.

This procedure was repeated 29 times during about 106 days and the contents of soluble nutrients in the changed sea water were measured occasionally. From the measured values, the amount of nutrients diffused into the sea water were computed. The cylinder used for this experiment is about 9.2 cm in diameter and about 40 cm in height. The monthly mean temperatures during the experiment were 10.4°C in March, 13.4°C in April and 16.9°C in May.

The results are summarized as follows: The soluble nutrients in mud were easily released into the sea water, and their amounts diffused were considerable in this experiment. The rate of diffusion for the nitrogen and phosphorus was higher than that for silica (Fig. 31) At the end of this experiment, the mud in the cylinder was divided into eight layers according to depth, and the vertical distribution of soluble nutrients in the mud was observed. The contents of ammonia-N or phosphate-P and silicate-Si in the upper layers were lower than initially and their contents increased with the depth of the mud. In

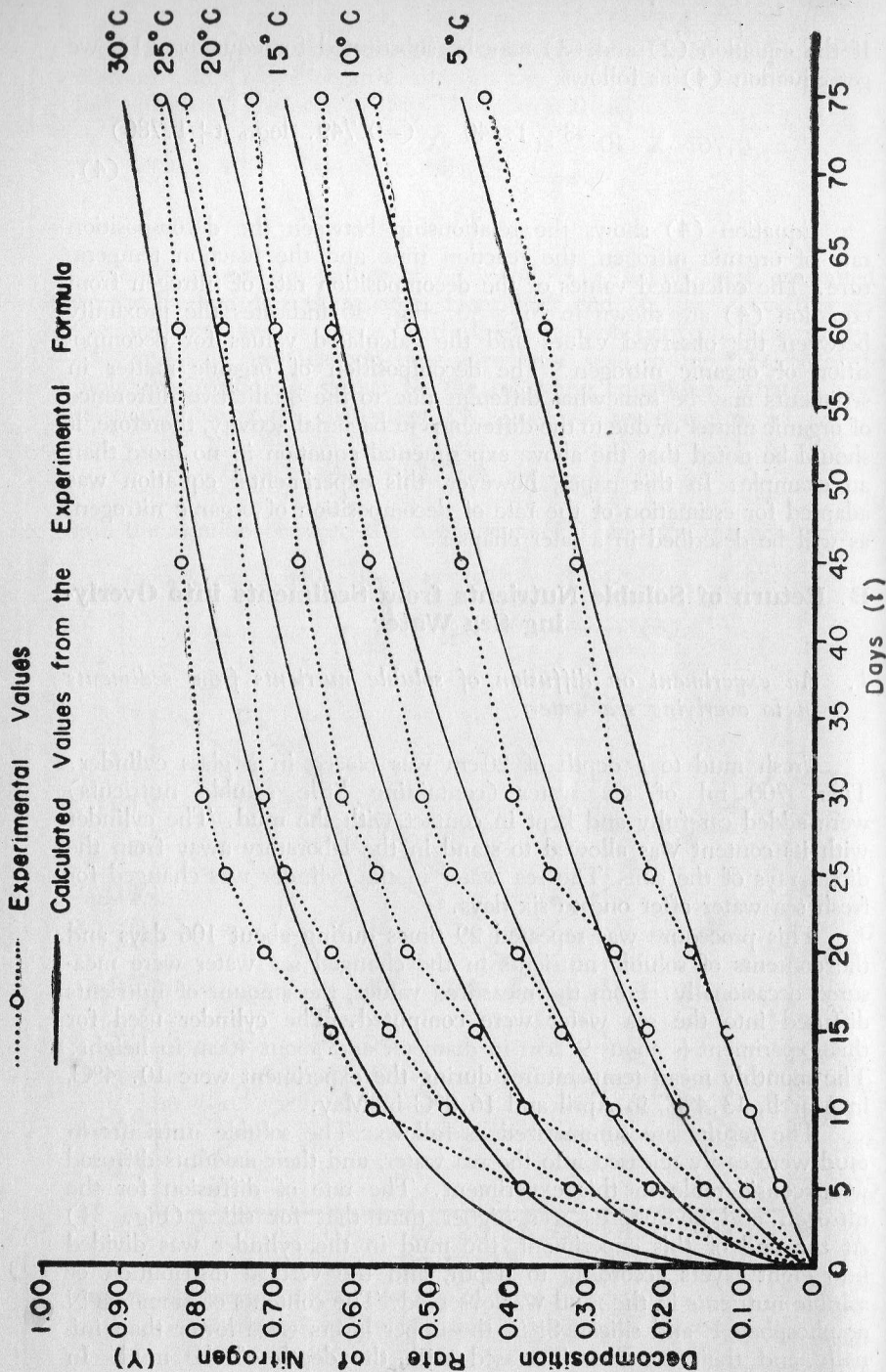


Fig. 30 — Relations of decomposition rate of organic nitrogen to reaction time and temperature

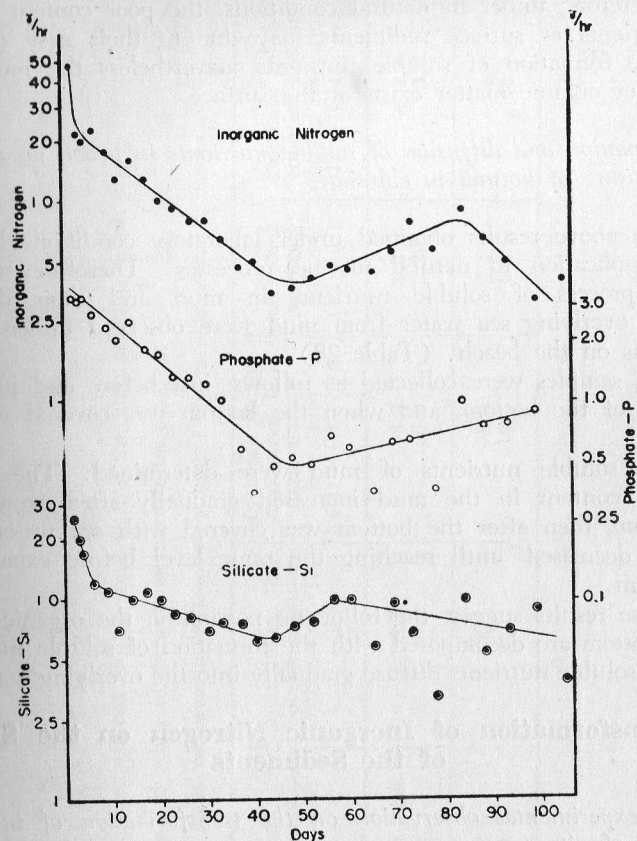


Fig. 31 — Relations of diffusion rate of soluble nutrients to standing time
Relações de difusão dos nutrientes solúveis num determinado tempo

Relation entre le rapport de diffusion et les éléments nutritifs solubles dans un temps donné

layers deeper than 10cm, there was practically no difference between the content before and after storage. It seems likely that phosphate-P and silicate-Si were diffused from the mud of the layer less than 10cm in depth, and those of ammonia-N were diffused from layer below 10cm. Such vertical distributions of soluble nutrients in mud are in good agreement with those in sediments under natural conditions as mentioned in previous section.

As will be seen from Table 27, the rate of diffusion was as follows: 30.8% inorganic nitrogen, 27.2% phosphate-P and 19.8% silicate-Si. Here, the rate of diffusion was expressed as the proportion of the diffused amount to the initial amount in the sample.

Therefore, under in natural conditions, the poor content of soluble nutrients at surface sediments may due to their easy diffusion after the formation of soluble nutrients, nevertheless the more high content of organic matter exists at the surface.

2. *Formation and diffusion of soluble nutrients in beach mud during exposure of bottom in ebb-tide*

The above results obtained under laboratory conditions have no direct application to natural marine processes. Therefore, the formation process of soluble nutrients in mud and their diffusion into the overlying sea water from mud were observed under natural conditions on the beach. (Table 28)

The samples were collected as follows; just before and just after exposure of the bottom, and when the bottom was covered with sea water.

The soluble nutrients of mud were determined. The soluble nutrients content in the mud increased gradually after exposure of the bottom, then after the bottom was covered with sea water, these contents decreased until reaching the same level before exposure of the bottom.

These results suggest the following possibility; the organic matter in the bottom are decomposed with the formation of soluble nutrients, then the soluble nutrients diffuse gradually into the overlying sea water.

C. Transformation of Inorganic Nitrogen on the Surface of the Sediments

1. *An experimental observation on the transformation of inorganic form of nitrogen*

An interesting and significant phenomenon was observed in the diffusion of nutrient elements from the mud mentioned above (Fig. 32)

In the early stage of the storage of mud and sea water, ammonia-N in the exchanged sea water was most abundant, while nitrite-N and nitrate-N were present in mere traces or entirely absent. After 30 to 35 days, ammonia-N disappeared and nitrite-N became strongly positive. Then, nitrate-N became abundant after about 40 days. After about 90 days, ammonia-N decreased remarkably and nitrite-N and nitrate-N became strongly positive, but nitrite-N was low as compared with nitrate-N.

Before storage, ammonia-N was, most abundant in the mud, although nitrite-N and nitrate-N were entirely absent.

However, it should be noted that at the end of the experimental period, both nitrite-N and nitrate-N were abundant in the upper layer of mud but decreased with depth, while ammonia-N increased with the depth of mud.

T A B L E 28

Variations of soluble nutrients in the covered and exposed bottom mud during the high and low tides.

Variação dos nutrientes solúveis na lama coberta e descoberta durante as marés altas e baixas

Variation des éléments nutritifs dans la base du fond, recouverte et decouverte durant les marées hauts et basses.

| Date | Element | Just before the bottom exposu- red (I) with water γ/g | Just before the bottom covered with water (II) γ/g | Increase in the exposed bot- tom during low tides (II) - (I) γ/g | In the covered bottom (III) γ/g | Decrease in the covered bottom during high tide (II) - (III) γ/g |
|------------------|--------------------------|---|--|---|---|--|
| June 17, 1953 | Phosphate—P Ammonia—N | 2.2 0 | 5.5 6.0 | 3.3 6.0 | 3.0 2.2 | 2.5 3.8 |
| Aug. 15, 1953 | Phosphate—P Ammonia—N | 2.6 1.5 | 8.1 12 | 5.5 10.5 | 2.1 1.2 | 6.0 10.8 |

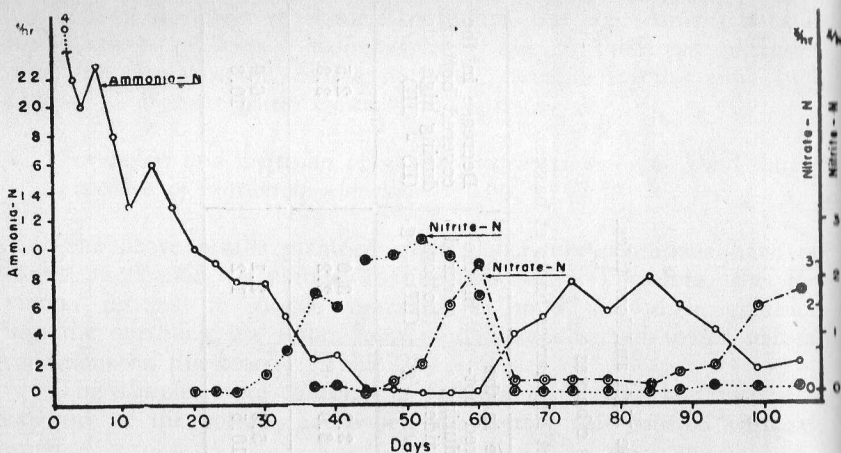


Fig. 32 — Experiment on transformation of inorganic nitrogen
 Experiência sôbre a transformação do nitrogênio inorgânico
 Expérience sur la transformation de l'azote minéral

From the following various reasons, this leads to the conclusion that nitrite-N and nitrate-N are formed in the upper layer of mud, and later diffuse into the overlying sea water. Namely, at the end of the experiment, i) high nitrite-N and nitrate-N in the mud column distributed only at the top mud layer, ii) nitrite-N and nitrate-N in the interstitial water at top mud were higher than two times as compared with those in the exchanged sea waters, iii) the exchange intervals of sea water very short days (only 3-6 days).

(The detailed discussion of this problem was done in the author's previous paper (Okuda, 1955))

2. Seasonal variation of inorganic nitrogen in interstitial water in sediments.

The observation was done once in a month for the period extending from June, 1955 to May '56. The interstitial water was separated from fresh mud by centrifugation.

The results are summarized as follows: In winter, the amount of ammonia-N in the interstitial water in the surface layer (0-2cm) was generally lower than that in deeper layers. In summer, on the other hand, ammonia-N in the surface layer was higher than that in deeper layers, but sometimes did not vary with depth.

The seasonal variation of the ammonia-N, and nitrate-N in the interstitial water showed a tendency to fluctuate similar to that of sea water. The high amount of ammonia-N was obtained in summer and

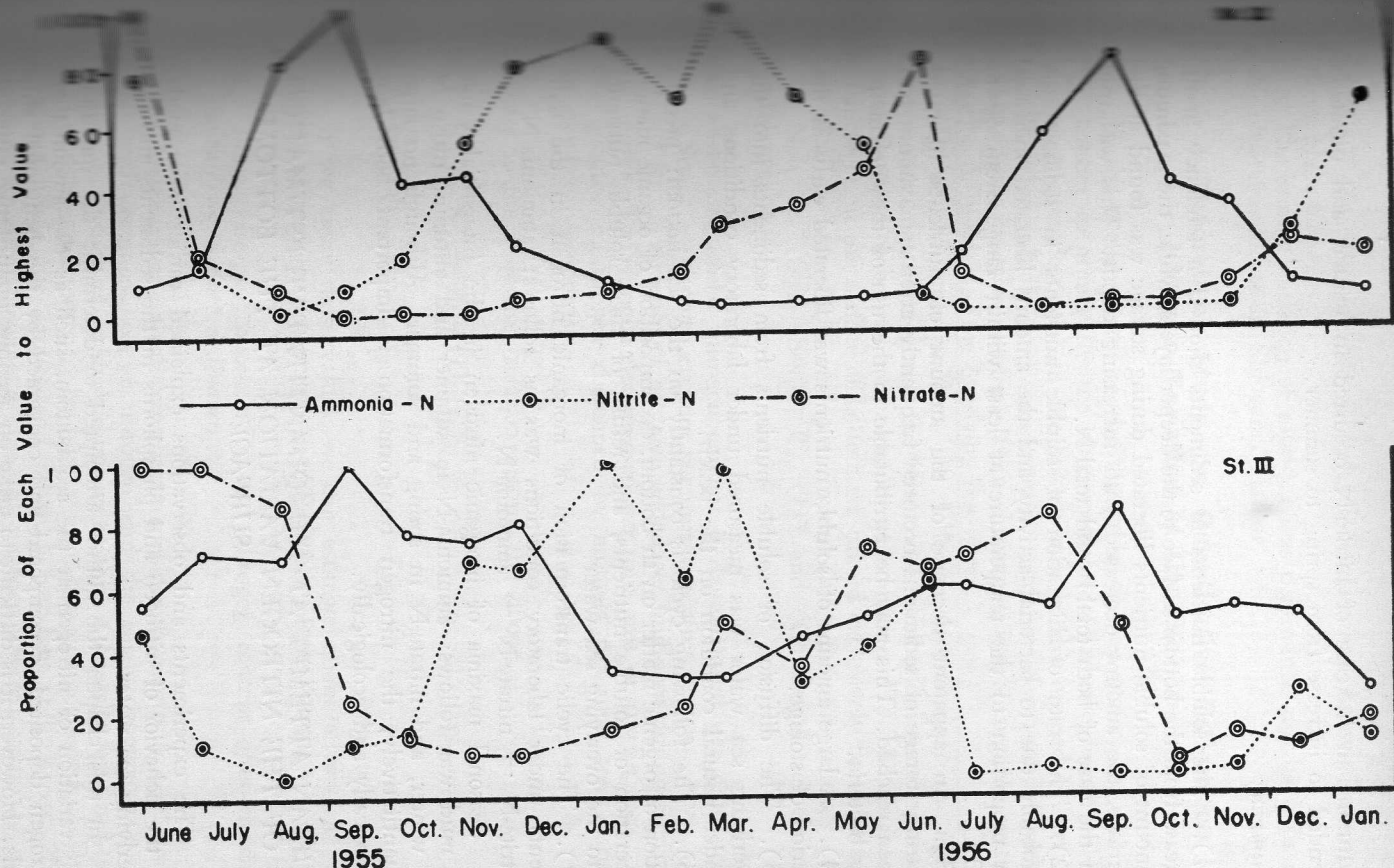


Fig. 33 — Seasonal variation of inorganic nitrogen in the interstitial water of sediments.
 Variação estacional de nitrogênio inorgânico na intersticial dos sedimentos
 Variation saisonnière de l'azote minéral dans l'eaursticial des sédiments

autumn, an increase of nitrite-N occurred in winter, and nitrate-N tended to increase from spring to summer.

Summary

(1). The soluble nutrients in sediments showed a tendency to increase from the bottom surface to the deeper layers, while, the maximum amount of soluble nutrients liberated during storage was found at the surface, the amount decreased with increasing depth. This was true in the case of both total-P and total-N.

(2). The rate of liberation of soluble nutrients in sediments is probably due to bacterial activity and the amount liberated increases in proportion to the temperature at least within range from 5° to 30°C.

(3). An apparent decrease of the amount of nutrients liberated during storage of sediments occurred frequently after a maximum had been reached. This may be attributable to the use of these elements by bacteria.

(4). A large amount of soluble nutrients was liberated early in the period of storage.

(5). The diffusion of soluble nutrients from sediments into the overlying sea water was measured under laboratory conditions and under natural condition on the beach.

(6). The following cycle is constantly on the sea bottom: precipitation of organic matter on the bottom, decomposition of organic matter, liberation of soluble nutrients, and return of these soluble nutrients into the overlying sea water.

(7). The cyclic transformation of inorganic nitrogen in the sediments under laboratory conditions was as follows: ammonia-N → nitrite-N → nitrate-N → ammonia-N.

Seasonal maxima of inorganic nitrogen in the interstitial water of mud was follows: ammonia-N in summer and autumn, nitrite-N in winter, and nitrate-N in spring and summer. Although no large quantitatively, the nitrogen transformation is important both biochemically and ecologically.

VIII. AN ATTEMPT AT THE QUANTITATIVE ESTIMATION OF THE NITROGEN VARIATION AT THE BOTTOM SURFACE

The experiments and observations explained earlier were made on the behavior of nitrogen and phosphorus in the sediments and the overlying sea water.

In this chapter the author attempted to determine the quantitative variation of nitrogen at the sea bottom, such as the amounts of nitrogen deposited, decomposed and consumed by the benthonic animals. However, it is difficult to make an accurate quantitative estimate

of these variations because of lack of fundamental knowledge about these phenomena.

The annual variation of nitrogen was determined on the basis of the observation data in Shiogama Harbor.

A. A Theoretical Study on Quantitative Estimation of Nitrogen Variation at the Bottom

In the cyclic process of the matter in the sea water, the rôle of the bottom is principally the decomposition of organic matter. The organic matter deposited on the bottom may be decomposed bacteriologically or chemically, and some may be eaten by benthonic animals. The soluble matters resulting from decomposition of organic matter may be diffused into the overlying sea water.

To simplify the problem, the following assumptions are made on the variation of nitrogen at the bottom: (1) The additions of nitrogen to the surface of bottom are caused by precipitation. (2) The decreases of nitrogen at the surface of bottom are caused exclusively bacterial and chemical decomposition and consumption by benthonic animals.

Now, let (S_0), (S_{tn}), (P), (D) and (C) denote respectively as follows;

S_0 Initial nitrogen content in bottom mud per unit area.

S_{tn} Nitrogen content per unit area after tn days.

P Amount of nitrogen added per unit area during tn days.

D Nitrogen decomposed per unit area during tn days.

C Nitrogen consumed by animals per unit area during tn days.

There is the following relation among the above,

$$S_{tn} - S_0 = P - (D + C)$$

$$D + C = (P + S_0) - S_{tn} \dots\dots(1)$$

If we know these values, we can estimate quantitatively the variations of nitrogen in tn days at the surface of the bottom.

1. Initial nitrogen content (S_0) and nitrogen content after tn days (S_{tn}) in surface sediments.

To estimate these values we must consider the depth as it relates to the rapid decomposition of nitrogen and the easily decomposable nitrogen in a study of as short duration as this. Generally speaking, the nitrogen content tends to be higher near the surface, lower of some distance below the surface and relatively constant still deeper. The layer of sediments having a constant nitrogen content vertically may

be indicated by the vertical distribution of nitrogen. Since the depth of sediments varies with topographical and oceanographical conditions, this must be determined for different localities. The easily decomposable nitrogen can be estimated from the nitrogen content in the surface layer and that in the deep layer which shows a constant value vertically. In this paper (So) and (Stn) will be estimated from the easily decomposable nitrogen per unit area according to depth of sediments.

2. Added nitrogen to the bottom during tn days (P)

The constituents deposited on the bottom, may be considered under three headings.

- (1) Terrigenous deposition carried by the river and wind.
- (2) Organic productive deposition consisting of plankton organisms (O. P. D.).
- (3) Reprecipitated deposition after floating from the bottom (R. D.).

The terrigenous deposits are omitted from this discussion, because of the measurement and the assumption of their amounts are hardly accurate. Furthermore, dissolved nitrogen is not considered in this discussion, even though a large amount of dissolved nitrogen from the land may flow into the sea.

The amount of nitrogen in the reprecipitated deposits (R.D.) at the observation position is not related to the net added nitrogen, because it is considered that the origin of the (R.D.) is the sediments floated from the same position. In consequence, it is presumed that the net added nitrogen consists of only the organic productive deposits (O.P.D.).

The measurement of the amount of deposits can be made by hanging tubes at the sea bottom. The deposits in tubes that were taken up after tn days, consist of the O.P.D. and the R.D.. When the tubes were taken up after tn days, the O.P.D. nitrogen in the tubes is the residual part and shows a lower value than the real value of the added nitrogen actually on the bottom, because the O.P.D. nitrogen is broken down by bacterial action while the tubes are hanging tn days.

The added nitrogen (P) during tn days, corresponds to the sum of the O.P.D. nitrogen precipitated on the bottom during the entire period, and this is different from the O.P.D. nitrogen remaining in the tubes after tn days.

They are distinguished as follows the O.P.D. remaining in the tubes after tn days is denoted as "residual organic productive deposits (residual O.P.D.)", on the other hand, on the supposition that the decomposition of the deposits did not occur during the hanging down, then, the O.P.D. is denoted as "total organic productive deposits (total O.P.D.)". At first we shall presume the residual O.P.D. and then the total O.P.D..

a. The presumption of nitrogen in residual O.P.D.

The following equation is used for calculations on the deposits that were contained in the tubes after tn days,

$$A \cdot a = B \cdot b + (A - B) \cdot b'$$

Here, A total weight of deposits on a dry matter basis (g),
 a nitrogen content of total deposits (%),
 B weight of residual O.P.D. (g),
 b nitrogen content of residual O.P.D. (%),
 A-B weight of R.D. (g),
 b' nitrogen content of R.D. (%).

equation (2) is as follows;

$$B = \frac{a - b'}{b - b'} \cdot A \dots\dots\dots (2)$$

We can calculate the weight of residual O.P.D. from the equation (2), then, amount of nitrogen may be calculated for (B x b).

(1) Weight and nitrogen content of whole deposits (A, a)

These values are found by the actual measurement.

(2) Nitrogen content of the R. D. (b')

From the assumption mentioned above, we may approximate the nitrogen content of surface sediments at the point for measuring b'.

(3) Nitrogen content of the residual O. P. D. after tn days (b')

At the first of the discussion of this problem, the conditions of decomposition and sinking of plankton to the bottom must be explained including the stage of the decomposition of plankton while sinking to the bottom and the sinking velocity of plankton as related to the oceanographical condition in the area. Munk (1953) and Okubo (1954, 1956) studied this theoretical problem in the ocean, but no such investigation has been made in the shallow sea. This may be due to the complexity of various conditions of the tides, weather etc. in the shallow water. Accordingly, as it is difficult that these factors are introduced into this discussion, let us simplify the problem as follows; i). The chemical composition of the O.P.D. just after settling in the tubes, is the same as the living conditions of plankton. ii). After precipitation of the O.P.D., they will begin to decompose immediately.

In accordance with this supposition (ii), the O.P.D. may be

decomposed more in the early than the later stage.

In the previous chapter, the following experimental equation on the decomposition rate of organic nitrogen was used.

$$Y = f(x, t) = 0.000767 t^{1.34} x^{(-0.749 \log_{10} t + 1.78)} \dots (3)$$

Here, Y — denotes the rate of decomposition of organic nitrogen, x — the temperature and t — the time.

It is assumed that the rate of decomposition of nitrogen in the O.P.D. may be estimated from the experimental equation (3). In the case of the presumption of (b) in the residual O.P.D., we must consider the variation of weight of O.P.D. at every moment. But, it would be no great error to think that the variation of weight in O.P.D. caused by the decomposition of organic matter may be small in a short period. Therefore, the presumption of (b) is made from the variation of the rate of change in nitrogen content without considering the variation of its weight. Furthermore, we may simplify the problems as follows: daily deposits are of constant quantity and the same chemical composition and the water temperature is constant during tn days.

Then, (β) denotes the nitrogen content of the O.P.D. immediately after settling and may be measured actually from nitrogen content of the plankton at the time.

After the deposits settled in the tubes, the nitrogen content of the O.P.D. (β) varies in inverse proportion to the rate of decomposition of nitrogen at every moment, and in general, after tn days with water temperature (x) ; (β) may become

$$\beta \cdot \{1 - f(x \cdot t)\}$$

As the decomposition ratio $(f(x \cdot t))$ of the nitrogen in daily O.P.D. may vary with the lapse of days from settlement to removal, the whole mean decomposition rate in tn days will become as follows:

$$\int_0^{tn} f(x \cdot t) dt / tn$$

And the mean residual rate will be

$$\int_0^{tn} \{1 - f(x \cdot t)\} dt / tn.$$

After tn days, consequently, the nitrogen content of residual O.P.D. is denoted approximately as follows

$$b = \frac{\beta \int_0^{tn} \{1 - f(x \cdot t)\} dt}{tn} \dots (4).$$

Then, if (A), (a) and (b') that can be actually measured and (b) of the equation (4) may be put into the equation (2), the residual O.P.D. (B) at that time can be computed. Furthermore, the nitrogen content of the residual O.P.D. will be obtained from the multiplication of (B) and (b).

b. The presumption of the nitrogen content in the total O.P.D. — (P)

From above the residual O.P.D., the nitrogen in the total O.P.D. (P) added in unit area during tn days, may be estimated. Let us assume that a constant amount of the O.P.D. is precipitated daily at the bottom during tn days, and (w) denotes the weight of the daily deposits, and the amount of nitrogen in total O.P.D. is denoted as $(w \cdot \beta)$. In general, then, the amount of nitrogen in the residual O.P.D. per a day is

$$w \cdot \beta \{1 - f(x \cdot t)\}$$

at water temperature (x) after t days. Since the amount of nitrogen of the O.P.D. precipitated daily on t_1 day, t_2 day, ..., $tn-1$ day and tn day, lapses respectively tn days, $tn-1$ day, ..., t_2 day and t_1 day, until the taking up of the tubes after tn days. The amount of nitrogen precipitated daily in the O.P.D. will be changed as follows with the lapse of time of hanging down. Thus the amount of nitrogen in each day will be shown respectively as $w \cdot \beta \{1 - f(x \cdot tn)\}$, $w \cdot \beta \{1 - f(x \cdot tn-1)\}$, ..., $w \cdot \beta \{1 - f(x \cdot t_1)\}$ with the lapse of days.

Accordingly, the amount of nitrogen of the residual O.P.D. (B.b) is shown by the following equation,

$$B.b = w \cdot \beta \int_0^{tn} \{1 - f(x \cdot t)\} dt \dots (5).$$

From the above equation (5), the following equation is introduced on the daily amount of nitrogen of the O.P.D.

$$w \cdot \beta = \frac{B.b}{\int_0^{tn} \{1 - f(x \cdot t)\} dt} \dots (6)$$

The weight (W) of the total O.P.D. that was precipitated during tn days is shown as $w \cdot tn$. Therefore, the nitrogen (P) in the total O.P.D. is shown as $W \cdot \beta$, and can be obtained the following equation (7).

$$P = W \cdot \beta = w \cdot tn \cdot \beta = \frac{B \cdot b \cdot tn}{\int_0^{tn} \{1 - (x \cdot t)\} dt} \dots\dots\dots (7)$$

3. The decomposed nitrogen (D)

The decomposed nitrogen (D) consists of the decomposed nitrogen (d_1) in the initial bottom sediments and the decomposed nitrogen (d_2) in the O.P.D. during tn days, that is,

$$D = d_1 + d_2$$

and (d_1) is denoted by the following equation

$$d_1 = So \cdot f(x \cdot tn) \dots\dots\dots (8).$$

As the (d_2) is the difference between the nitrogen (P) in the total O.P.D. and the nitrogen (B.b) in the residual O.P.D., the following equation is obtained on the (d_2) from the above equations.

$$\begin{aligned} d_2 &= W \cdot \beta - B \cdot b = w \cdot tn \cdot \beta - w \cdot \beta \int_0^{tn} \{1 - f(x \cdot t)\} dt \\ &= w \cdot \beta \int_0^{tn} f(x \cdot t) dt \dots\dots\dots (9) \end{aligned}$$

Consequently, the whole decomposed nitrogen (D) can be obtained from the following equation

$$D = d_1 + d_2 = So \cdot f(x \cdot tn) + w \cdot \beta \int_0^{tn} f(x \cdot t) dt \dots (10)$$

4. The nitrogen consumed (C) by the benthonic animals

The nitrogen used (C) by the benthonic animals during tn days may be obtained from putting (So), (Stn), (P) and (D) into the equation (1), that is,

$$C = (P+So) - (Stn+D) \dots\dots\dots (11)$$

While, since the consumed nitrogen (C) is obtained from the difference between the other values, high accuracy may be not expected as compared with that of the other measured and presumed values.

B. AN Annual Variation of Nitrogen at the Bottom Surface in Shiogama Harbor

From the above theoretical discussion, nitrogen variations at bottom surface were estimated from the data of Shiogama Harbor as follows.

1. Methods of measurement

The mud depth concerned in the nitrogen cyclic process within a relatively short time was assumed to be 3 cm from the surface from previous results, because abundant amounts of fresh organic matter are distributed only within a few centimeters of the bottom surface. Sediments were sampled once monthly, samples were filtered through a 1 mm sieve while wet, and the total nitrogen was determined after drying. The calculation of easily decomposable nitrogen was made as mentioned above. The data mentioned in chapter VI were used in order to estimate the nitrogen of the O.P.D..

The results are shown in Table 29. For convenience of comparison, these values are shown as calculated monthly values. The nitrogen content (b') of the reprecipitated deposits (R.D.) was approximated from the nitrogen content of surface sediments that were collected from a layer of a few mm thick (once monthly). As the nitrogen content of plankton was not measured monthly, the nitrogen content (β) of the O.P.D. was estimated at 7.8% from the results of the author and other investigators.

2. Results

a. Monthly variation of the decomposable and consumable nitrogen (So+P)

Seasonal variations in (So+P) are given in Fig. 34 Table 29. The highest values (8.2 - 9.1 N-g/m²/month) were found from May to July. The lowest values (3.8 - 4.8 N-g/m²/month) occurred from September to March. Intermediate values (about 6 N-g/m²/month) were obtained in April and August.

b. Monthly variation of the decomposed and consumed nitrogen (C+D)

The maximum value of (C+D) was found in August with value of 6.0 N-g/m²/month, while, the minimum value (0.89 N-g/m²/month) was obtained in February (Fig. 35).

TABLE 29

Seasonal variation of various nitrogen at bottom surface.

Variação estacional de diferentes nitrogênios na superfície do fundo.

Variations saisonnières des différents azote à la superficie du fond.

| Month | S _n | P | S _n + P | C + D | d ₁ | d ₂ | D | C | Stn |
|------------|----------------|--------|--------------------|--------|----------------|----------------|--------|--------|-------|
| June, 1956 | 3,380 | 5,730 | 9,110 | 4,910 | 1,620 | 2,230 | 3,850 | 1,060 | 4,200 |
| July, | 4,110 | 4,120 | 8,230 | 5,970 | 2,610 | 1,800 | 4,410 | 1,560 | 2,260 |
| Aug., | 2,170 | 4,080 | 6,250 | 5,520 | 1,430 | 2,010 | 3,440 | 2,080 | 730 |
| Sep., | 860 | 3,760 | 4,620 | 3,770 | 540 | 1,680 | 2,220 | 1,560 | 850 |
| Oct., | 810 | 3,940 | 4,750 | 2,580 | 430 | 1,470 | 1,900 | 680 | 2,170 |
| Nov., | 2,270 | 2,030 | 4,300 | 1,590 | 760 | 670 | 1,430 | 170 | 2,710 |
| Dec., | 2,600 | 1,410 | 4,010 | 1,480 | 720 | 220 | 940 | 550 | 2,530 |
| Jan., 1957 | 2,560 | 1,280 | 3,840 | 990 | 520 | 170 | 690 | 300 | 2,850 |
| Feb., | 2,850 | 1,050 | 3,900 | 890 | 530 | 110 | 640 | 250 | 3,010 |
| Mar., | 3,020 | 1,600 | 4,620 | 1,320 | 760 | 210 | 970 | 350 | 3,300 |
| Apr., | 3,290 | 2,530 | 5,820 | 2,570 | 1,140 | 680 | 1,820 | 750 | 3,250 |
| May, | 3,250 | 4,910 | 8,160 | 4,550 | 1,340 | 1,750 | 3,090 | 1,460 | 3,610 |
| Total | | 36,440 | 67,610 | 36,140 | 12,400 | 13,000 | 25,400 | 10,770 | |

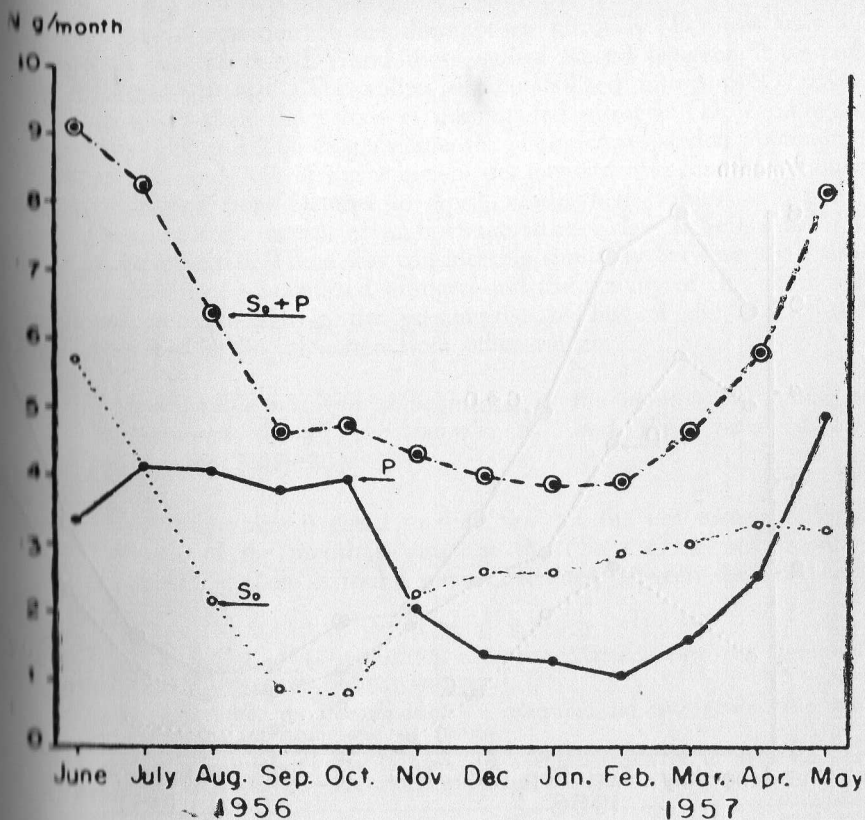


Fig. 34 — Monthly variation of decomposable and consumable nitrogen
 Variação mensal de nitrogen decomponível e consumível
 Variation mensuelle de l'azote décomposable et consommable

So.....

Decomposable and consumable nitrogen at beginning of the month

Nitrogênio decomponível e consumível no início do mês
 Azote décomposable et consommable au début du mois

P.....

Decomposable and consumable nitrogen, deposited during a month

Nitrogênio decomponível e consumível, depositado durante um mês
 Azote décomposable et consommable, déposé durante un mois

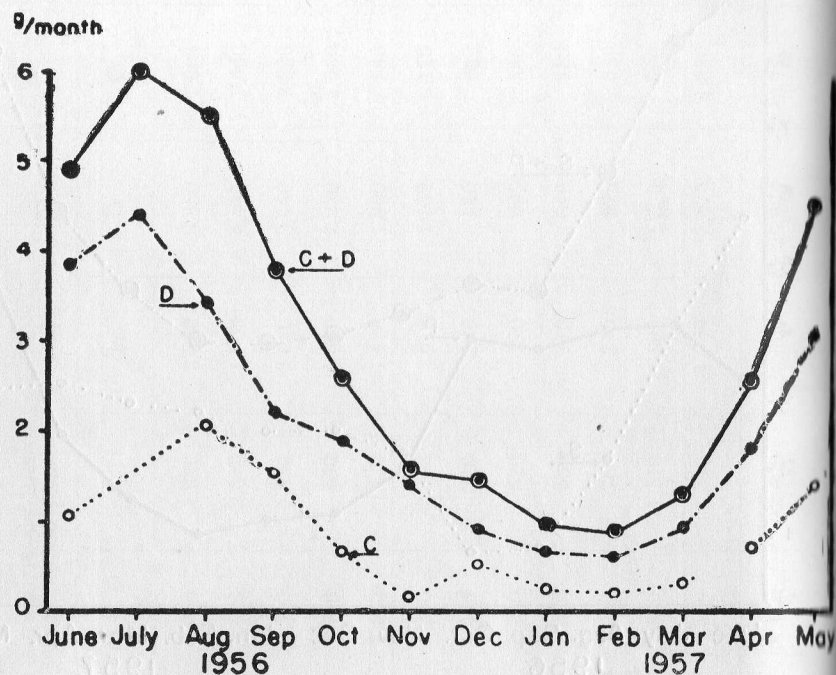


Fig. 35 — Monthly variation of decomposed and consumed nitrogen
Variação mensal de nitrogênio decomposto e consumido
Variation mensuelle d'azote décomposé et consommé

D.....

Decomposed nitrogen in a month
Nitrogênio decomposto num mês
Azote décomposé en un mois

C.....

Consumed nitrogen in a month
Nitrogênio consumido num mês
Azote consommé en un mois

Seasonal variation of the decomposed nitrogen (D) was very similar to that of (C+D) and these values ranged between 0.64 and 4.4 N-g/m²/month. The values of metabolized nitrogen (C) were always lower than the values of decomposed nitrogen (D), and were between 0.17 and 2.08 N-g/m²/month. They corresponded approximately to 12% and 70% of the values of decomposed nitrogen. Low values were obtained from October to April, while, high values were generally found in the season of high temperature (May to September) as might be expected. There was considerable similarity between the seasonal variations of metabolized nitrogen and the activity of the benthonic animals, even though in the presumptive method of the metabolized nitrogen had to be calculated from other values.

c. Decomposable nitrogen at beginning of the month (S_0), nitrogen decomposed during the month (d_1) and their ratio (d_1/S_0) (Fig. 36, Table 30)

The (S_0) value is equal to the (S_{tn}) of the last month and the (S_{tn}) value of the month is equal to the (S_0) of the next month. In the table 29, there is found some difference between the (S_0) and

T A B L E 3 0

Seasonal variation of decomposition rate and consume rate (by benthonic animals) of nitrogen on bottom surface.

Variação estacional da decomposição e consumo de nitrogênio pelo animais bentônicos na superfície do fundo.

Variations saisonnières entre le taux de décomposition et le taux de consommation en azote par les animaux benthiques à la superficie du fond.

| Month | D+C/ S_0 +P(D) | 100—(I) | d_1/S_0 | d_2/P | D/ S_0 +P | C/ S_0 +P | C/D |
|------------|------------------|---------|-----------|---------|-------------|-------------|-----|
| June, 1956 | 54 | 46 | 48 | 39 | 42 | 12 | 28 |
| July, | 73 | 27 | 64 | 44 | 54 | 19 | 35 |
| Aug., | 88 | 12 | 66 | 49 | 55 | 33 | 60 |
| Sep., | 82 | 18 | 63 | 45 | 48 | 34 | 70 |
| Oct., | 54 | 46 | 53 | 37 | 40 | 14 | 36 |
| Nov., | 37 | 63 | 33 | 33 | 33 | 4 | 12 |
| Dec., | 37 | 63 | 28 | 16 | 23 | 14 | 59 |
| Jan., 1957 | 26 | 74 | 20 | 13 | 18 | 8 | 43 |
| Feb., | 23 | 77 | 19 | 10 | 16.5 | 6.5 | 39 |
| Mar., | 29 | 71 | 25 | 13 | 21 | 8 | 36 |
| Apr., | 44 | 56 | 35 | 27 | 31 | 13 | 41 |
| May., | 56 | 44 | 41 | 36 | 38 | 18 | 47 |

the (S_{tn}) of the last month. However, this difference has not important mean because this was made through the computation of the

monthly amount. The maximum value was observed in July with 4.1 N-g/m^2 , the minimum values ($0.81\text{-}0.86 \text{ N-g/m}^2$) were obtained in September and October. In the other month these values fluctuated narrowly from $2\text{-}3 \text{ N-g/m}^2/\text{month}$.

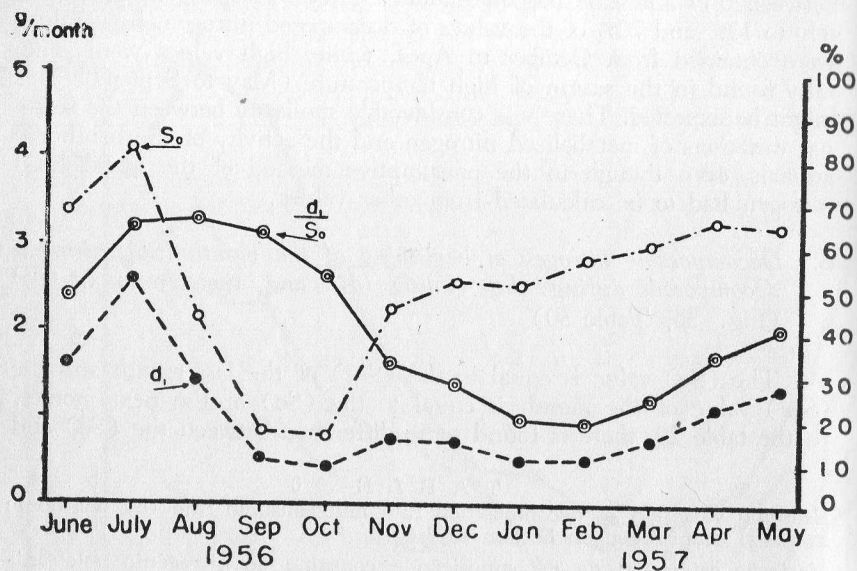


Fig. 36 — Monthly variation of decomposable nitrogen at beginning of the month (S_o), its decomposed nitrogen in the month (d_1) and decomposition rate (d_1/S_o)

Variação mensal de nitrogênio decomponível no início do mês (S_o), nitrogênio decomposto durante o mês (d_1) e relação de decomposição (d_1/S_o)

Variation mensuelle de l'azote décomposable au début du mois (S_o), l'azote décomposé dans le mois (d_1) et le rapport de décomposition (d_1/S_o)

As given in formula (1), (S_o) corresponds to the difference in the last month between the decomposable nitrogen (S_o+P) and the decomposed and consumed nitrogen ($C+D$). Therefore, the narrow fluctuation of (S_o) in the month before of these every month excepting July, September and October may be attributable to the approximate values in the difference between the values in the two fractions.

The highest value of (S_o) in July is based on the fact that the values of the added nitrogen (P) was more large than the decomposed nitrogen (D) in June. The lowest values of September and October were caused by that (P) were less than (D) in August and September respectively. The highest value of (d_1) was observed in July like (S_o),

and in the all another months except July these values showed little fluctuation.

In the season of high temperature (May to September), (d_1) values changed generally in proportion to (S_o) values, on the other hand, in the seasonal of low temperature (from October to March), these values were not proportionate to (S_o) values. The rate of decomposition of organic nitrogen was low in the latter season. The minimum value of (d_1/S_o) was 19% in February, the maximum value of (d_1/S_o) was 19% in August, and from July to October these values were above than 50%.

Therefore, these results indicate that more than half of the nitrogen (S_o) may be returned to overlying sea water during the time from July to October, and in the other months the nitrogen returned may be less than half of the (S_o).

d. Added nitrogen (P) decomposed nitrogen (d_2) and their ratio (d_2/P). (Fig. 37)

The seasonal cycle in (P) is divided clearly into two periods,

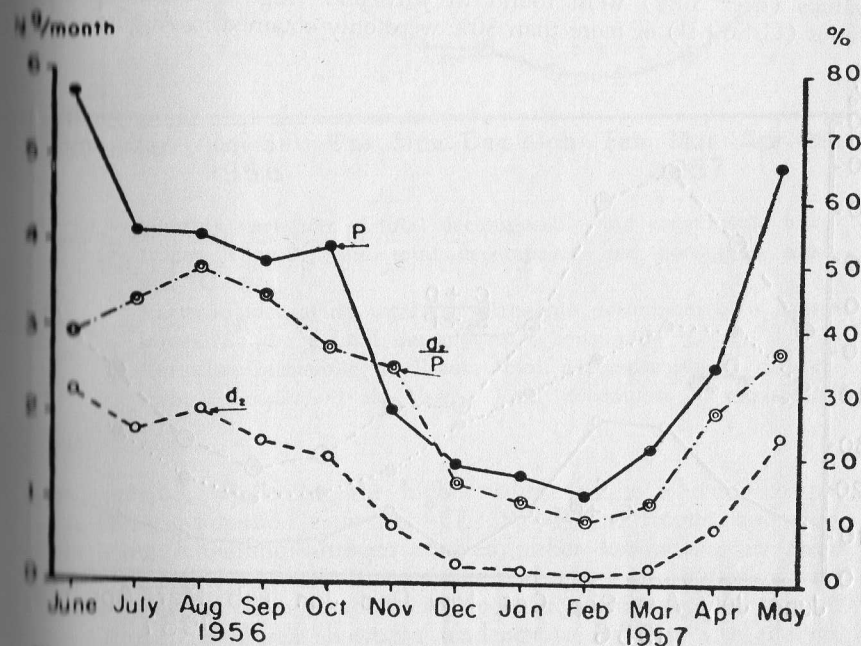


Fig. 37 — Monthly variation of deposited nitrogen (P), its decomposed nitrogen (d_2) and decomposition rate (d_2/P)

Variação mensal de nitrogênio depositado (P), nitrogênio decomposto (d_2) e relação de decomposição (d_2/P)

Variation mensuelle de l'azote déposé (P), l'azote décomposé (d_2) et le rapport de décomposition (d_2/P)

namely, the high period (from May to October) with values ranging between 3.8 – 5.7 N-g/m²/month and the low period (from November to next April) with values ranging between 1.1 – 2.5 N-g/m²/month

The seasonal variation of (d_2) closely parallels that of (P), although the difference between the maxima and minima of (d_2) is less than that of (P).

The seasonal variations of d_2/P were similar to those in d_1/So , namely, the lowest value was obtained in February and the highest value in August. During the year, values of d_2/P over 50% were not observed, therefore over half of the monthly added nitrogen, may remain on the bottom without returning to sea water during the month, and this nitrogen may be decomposed during next month.

e. *Interrelationship of the monthly variation of each fraction* (Fig. 38 and 39)

High proportions of the whole decomposed nitrogen (D/P) were obtained (more than 40%) from June to October, the highest values (over 50%) were found in July and August. Consumption ratios ($C/So+P$) of more than 30% were only obtained in August and

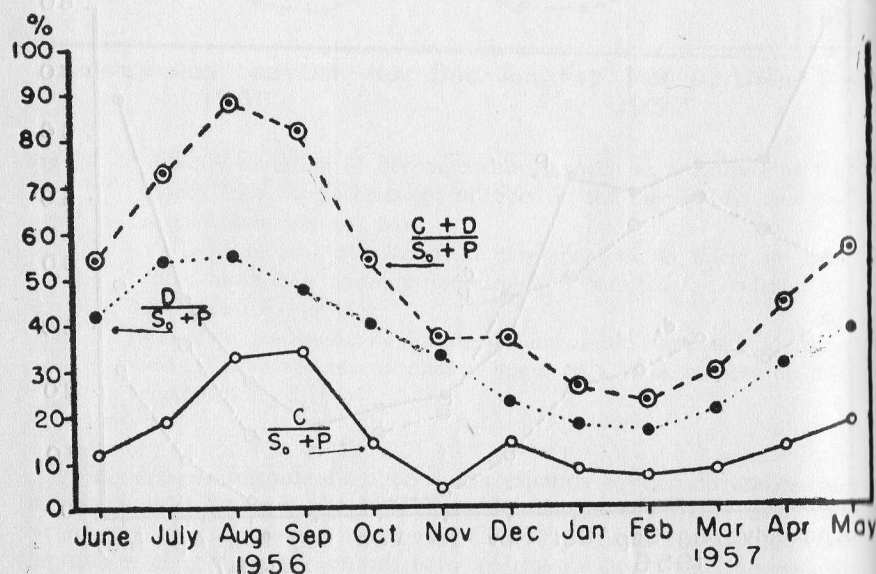


Fig. 38 — Monthly variation of total decomposition rate ($D/So + P$) and consumption rate ($C/So + P$)
 Variação mensal da relação de decomposição total ($D/So + P$) e relação de consumo ($C/So + P$)
 Variation mensuelle du rapport total de décomposition ($D/So + P$) et du rapport de consommation ($C/So + P$)

September, and the ratio in other months showed values less than 20% with less than 10% in November, January, February and March.

The highest values of ($D+C/So+P$) (more than 50%) were obtained from May to October including values over 80% in August

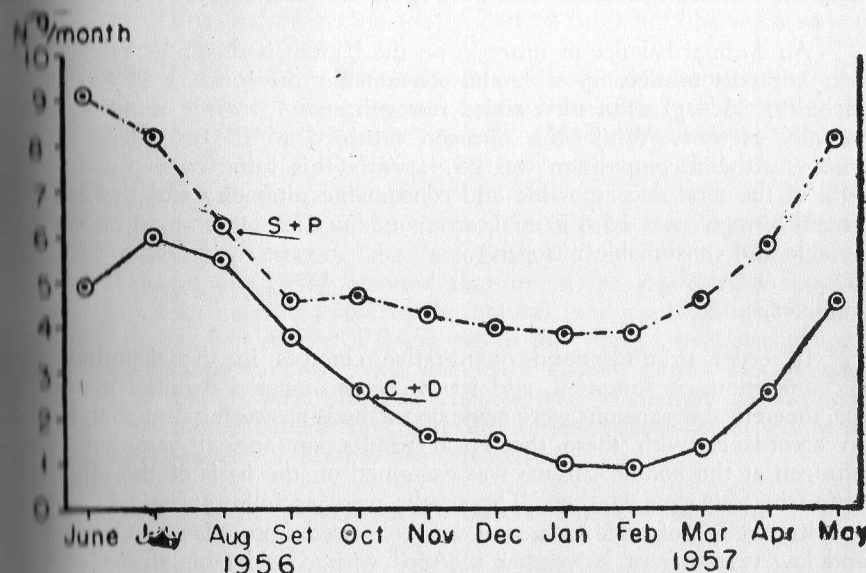


Fig. 39 — Monthly variation of total decomposable and consumable nitrogen ($So+P$), and total decomposed and consumed nitrogen ($C+D$)
 Variação mensal do total de nitrogênio decomponível e consumível ($So+P$) e total decomposto e consumido ($C+D$)
 Variation mensuelle de l'azote total décomposable et consommable ($So+P$) et de l'azote total décomposé et consommé ($C+D$)

and September. Reflecting the higher values of the whole decomposition and consumption ratio ($D+C/So+P$) in August and September, the remaining nitrogen showed rather low values in these months, and this resulted in low values of (So) in September and October. On the other hand, the nitrogen remaining on the bottom from October to March showed a tendency to increase with the decreased rate of decomposition and consumption.

Added nitrogen on the bottom accumulated gradually from October in March. Active decomposition of nitrogen due to higher water temperature decreased the accumulated nitrogen from April onward.

In view of the results above mentioned it may be concluded that from May to October, the decomposed and consumed nitrogen ($D+C$)

on the bottom exceeds the accumulated nitrogen $(So+P) < (D+C)$, while, from November to April the accumulated nitrogen exceeds the decomposed and consumed nitrogen.

C. An Annual Balance of Nitrogen at the Bottom Surface

An Annual balance of nitrogen on the bottom is shown as follows: The annual total decomposable and consumable nitrogen was 39.8 g/m^2 including 36.4 g/m^2 of total added nitrogen and 3.4 g/m^2 of nitrogen initially present. While the nitrogen returned to the overlying sea water by the decomposition was 25.4 g/m^2 (this value corresponds to 64% of the total decomposable and consumable nitrogen) and the consumed nitrogen was 10.8 g/m^2 (corresponds to 27% of the total decomposable and consumable nitrogen).

Summary

In order to understand quantitative changes in the deposition, decomposition, consumption, and return of decomposed material to the sea, theoretical discussions were made on methods measuring and analysis. In accordance with these theoretical results, an annual variation of nitrogen at the bottom surface was examined on the basis of the observation in Shiogama Harbor. The results were as follows:

1. High values of added nitrogen were observed from May to October and low values from November to April with considerable differences between the two periods.
2. The whole decomposition proportion showed values less than 50% except in July and August. Nitrogen existing at the beginning of the month was decomposed more than half during from May to October and less than half during the other six months.
3. The amount of consumable nitrogen was high in May to September and low during the season of low water temperature.
4. Organic nitrogen was decomposed or consumed faster than it was deposited from May to October and slower from November to April.
5. The annual potential decomposition and consumption of nitrogen was 39.8 g/m^2 . This is the sum of nitrogen existing at the beginning of the observation (3.4 g/m^2) and the nitrogen added during the year (36.4 g/m^2). 25.4 g/m^2 (64%) of the total potential decomposable and consumable nitrogen was decomposed and 10.8 g/m^2 (27%) was consumed by benthonic animals during the year.

IX. A CYCLE OF NUTRIENT SUBSTANCES IN THE ZOSTERA AREA

A large area of the bottom of Matsushima Bay is covered with *Zostera marina*. As mentioned earlier, the chemical and physical properties of the sea water and the sediments in Matsushima Bay are affected by the life-cycle of *Zostera*.

The enormous amount of *Zostera* on the bottom influences the growth of cultured oysters because it decreases the velocity of the current and reduces the area for oyster culture. On the other hand, the *Zostera* zone is a convenient habitat for young fishes.

Petersen (1918) calculated quantitative food relations of important animals in coastal waters where *Zostera* furnished the main source of primary food.

The relationship between the life-cycle of *Zostera* and the chemical and physical properties was studied by Imai, et al (1951) in Mangoku-ura (Miyagi, Japan). Arasaki (1950) reported the relation between the life-cycle of *Zostera* and its productions, with the results of morphological observation.

It is important to explain the ecological conditions in the *Zostera* area in order to estimate the biological productivity in Matsushima Bay. Imai et al (1951) reported that the naked non-colored flagellates played an important rôle in the natural production of seed oysters, and the abundant supply of flagellates in the Mangoku-ura was supported by decomposition of a vast amount of *Zostera* during the breeding season of the oysters. In this chapter, the circulation of nutrient substances in the *Zostera* zone, and the nutrient substances in sediments and the life-cycle of *Zostera* are reported.

A. A Life-Cycle of El-Grass, *Zostera Marina*

The height and dry weight of *Zostera* were observed monthly. The average values per plant represent measurements on about one hundred plants. These results are shown in Fig. 40 and Tab. 31.

There is a good agreement in the seasonal succession of height and

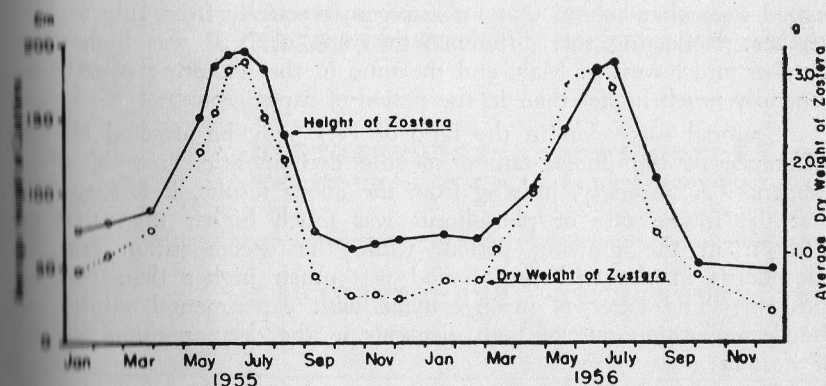


Fig. 40 — Seasonal variation of height and dry weight of *Zostera*
 Variação estacional da altura e peso seco da *Zostera*
 Variation saisonnière de la hauteur et du poids sec des *Zostera*

dry weight of the plant during the years 1955 and 1956. Apparently water temperature influenced greatly on the life-cycle of *Zostera*.

Zostera grows rapidly from March until the middle or end of June. After reaching maximum growth, the leaves and stems of *Zostera* begin to wither rapidly, and fall to the bottom.

Later, most the dead leaves and stems are carried from the area of growth to the inside or outside of the bay by water movements caused by strong north-westerly winds. From September to the next March, *Zostera* practically stops growing although new sprouts begin to emerge at the end of November.

The average height in the maximum growth period reached about 200 cm, while in the stagnant period it receded to 50-60 cm, and remained at this height till the beginning of March.

The dry weight of *Zostera* fluctuated in proportion to the its height from about 3.0g at the maximum (beginning of July) to 0.36-0.5g at the minimum (October to December).

B. Seasonal Variation of Nitrogen Content and Phosphorus Content in *Zostera*

1. Nitrogen and phosphorus contents and these absolute amounts per plant in the aquatic part

The results obtained are shown in Table 31, Fig. 41 and 42. The seasonal changes of the nitrogen and phosphorus showed an inverse relation to those of height and dry weight. The contents of these elements were highest during the dormant season and showed minimal values in the stage of rapid growth.

Although the curves for nitrogen and phosphorus content were rather similar, in the withering stage the rising curve for phosphorus lagged somewhat behind that for nitrogen, especially from July to November. Reflecting this difference the ratio of N:P was highest in October and lowest in May, and the ratio in the withering period was generally much higher than in the period of rapid growth.

Seasonal succession in the ratio of N:P may be affected by the difference of the intake rate or of the decomposition rate of these elements. Accordingly, judging from the above results, it is suggested that the intake rate of phosphorus was much higher than that of nitrogen in the growing period, while the decomposition rate of phosphorus in the withering period was much higher than that of nitrogen. The latter is in agreement with experimental results on the decomposition rate of both elements in the decomposition process of *Zostera*.

The seasonal changes in the nitrogen and phosphorus amounts per plant closely paralleled those of height and dry weight of *Zostera*, as seen in Fig. 42. While the maximum value of phosphorus per plant occurred earlier than that of the height and dry weight in both years

| Date | Height cm | Dry weight | | Total-N | | | Total-P | | | N/P |
|------|--------------|------------|------|---------------|----------|------|---------------|----------|------|-----|
| | | g/plant | + | Contents % | mg/plant | + | Contents % | mg/plant | + | |
| 1955 | Jan. 19 | 0.82 | 26.5 | 1.78 | 14.6 | 34.2 | 0.389 | 3.19 | 34.0 | 4.6 |
| | Feb. 14 | 0.95 | 30.7 | 1.62 | 15.4 | 36.0 | 0.339 | 3.22 | 34.3 | 4.8 |
| | Mar. 28 | 1.28 | 41.4 | 1.37 | 17.5 | 40.9 | 0.318 | 4.07 | 43.3 | 4.3 |
| | May. 16 | 2.14 | 69.2 | 1.06 | 22.7 | 53.0 | 0.298 | 6.38 | 67.8 | 3.6 |
| | June 2 | 2.57 | 83.2 | 1.20 | 30.8 | 72.0 | 0.303 | 7.79 | 83.0 | 4.0 |
| | June 15 | 3.04 | 98.4 | 1.28 | 38.9 | 90.9 | 0.298 | 9.06 | 96.5 | 4.3 |
| | July 1 | 3.09 | 100 | 1.34 | 41.4 | 96.7 | 0.263 | 8.13 | 86.6 | 5.1 |
| | July 18 | 2.52 | 81.6 | 1.55 | 39.1 | 91.4 | 0.275 | 6.93 | 73.8 | 5.6 |
| | Aug. 11 | 2.05 | 66.5 | 1.57 | 32.2 | 75.2 | 0.291 | 5.97 | 63.6 | 5.4 |
| | Sep. 12 | 0.72 | 23.3 | 1.91 | 13.8 | 32.2 | 0.327 | 2.35 | 25.0 | 5.8 |
| | Oct. 17 | 0.54 | 17.5 | 2.69 | 14.5 | 33.9 | 0.337 | 1.82 | 19.4 | 8.0 |
| | Nov. 11 | 0.54 | 17.5 | 2.66 | 14.4 | 33.6 | 0.418 | 2.26 | 24.1 | 6.4 |
| | Dec. 5 | 0.51 | 16.6 | 2.49 | 12.7 | 29.7 | 0.441 | 2.25 | 24.0 | 5.6 |
| 1956 | Jan. 18 | 0.67 | 21.6 | 2.56 | 17.2 | 40.2 | 0.434 | 2.91 | 31.0 | 5.8 |
| | Feb. 23 | 0.71 | 23.0 | 2.13 | 15.1 | 35.3 | 0.433 | 3.07 | 32.7 | 4.9 |
| | Mar. 12 | 1.05 | 34.0 | 1.94 | 20.4 | 47.7 | 0.389 | 4.08 | 43.4 | 5.0 |
| | Apr. 19 | 1.66 | 53.7 | 1.40 | 23.2 | 54.2 | 0.318 | 5.28 | 56.2 | 4.4 |
| | May 21 | 2.88 | 93.6 | 1.18 | 34.0 | 79.4 | 0.286 | 8.24 | 87.8 | 4.1 |
| | June 19 | 3.08 | 99.7 | 1.28 | 39.4 | 92.1 | 0.305 | 9.39 | 100 | 4.2 |
| | July 9 | 2.85 | 95.8 | 1.50 | 42.8 | 100 | 0.322 | 9.18 | 97.8 | 4.6 |
| | Aug. 22 | 1.24 | 40.1 | 1.65 | 20.5 | 47.9 | 0.229 | 3.71 | 39.6 | 5.5 |
| | Oct. 3 | 0.77 | 24.9 | 2.09 | 16.1 | 37.6 | 0.300 | 2.31 | 24.6 | 7.0 |
| | Dec. 20 | 0.36 | 11.7 | 3.01 | 10.8 | 25.2 | 0.499 | 1.80 | 19.2 | 6.0 |
| | 1957 | | | | | | | | | |
| | Mar. 20 | 0.70 | 22.6 | 1.89 | 13.2 | 30.8 | 0.377 | 2.64 | 28.1 | 5.0 |
| | May 22 | 2.25 | 72.8 | 1.37 | 30.8 | 72.0 | 0.343 | 7.72 | 82.2 | 4.0 |

+ Relative proportion of each to the highest value represented as 100.

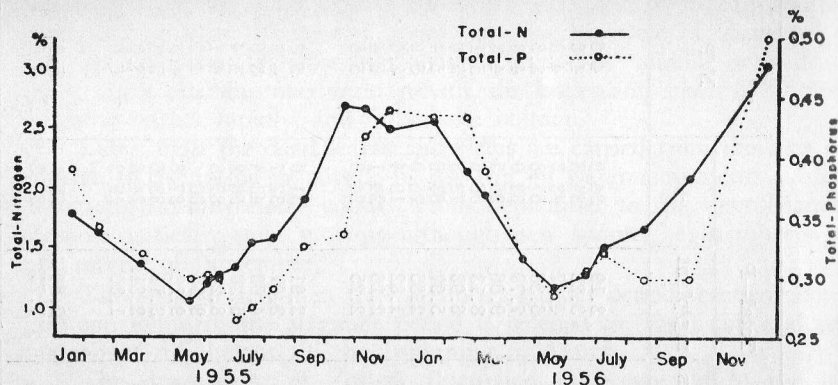


Fig. 41 — Seasonal variation of nitrogen content and phosphorus content in the aquatic part of *Zostera*
 Variação estacional do nitrogênio e fósforo na parte aquática da *Zostera*
 Variation saisonnière de la teneur en azote et en phosphore contenue dans les parties aquatique de *Zostera*

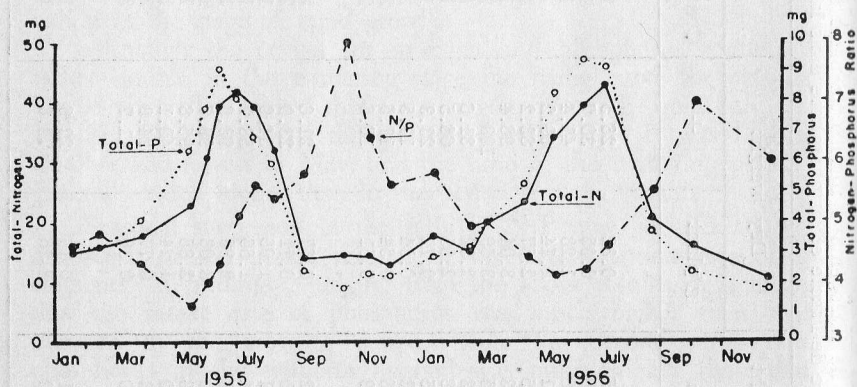


Fig. 42 — Seasonal variation of absolute content of nitrogen and phosphorus in the aquatic part
 Variação estacional do conteúdo absoluto de nitrogênio e fósforo na parte aquática em cada planta
 Variation saisonnière en azote et en phosphore total dans la partie aquatique de chaque plante

(1955,1956), the maximal value of in nitrogen was close agreement with that of the latter.

2. The contents of nitrogen and phosphorus in the subterranean part

Maximal and minimal values of nitrogen and phosphorus contents in the subterranean part were much lower than those in the aquatic part.

As shown in Table 32, the nitrogen and phosphorus in the subterranean part were estimated on three fractions such as new stem, old stem and root hair. The contents of nitrogen and phosphorus in the new subterranean stem and in root hair showed considerably seasonal variation, but in the old subterranean stem the variation was slight. This indicates that the old subterranean stem had lost already its vital function.

The phosphorus content in the new subterranean stem was generally much higher than in the root hair while the nitrogen contents in these fractions were quite similar.

The highest contents of nitrogen and phosphorus in the new subterranean stem occurred in December and the lowest in May. This was true on the aquatic part too. After the withering of *Zostera*, the phosphorus and nitrogen contents in the subterranean stem began to increase gradually till reaching the highest value in December. This may indicate that these elements are accumulated in the subterranean stem for the next growing stage of aquatic part. The contents of these elements in the root hair showed only slight seasonal variation in comparison with those in the subterranean stem. The ratio of N/P was quite different between the three fractions in the subterranean part, that is, 8.1-9.1 in the old stem, 2.2-5.1 in the new stem and 6.7-10.8 in the root hair. The ratios of N/P in the subterranean stem and in root hair were low in the growing period, and increased gradually from the withering stage to the beginning of growing stage.

The relative contents of nitrogen and phosphorus, and the ratio of N/P, in different parts of *Zostera* were as follows:

Nitrogen Aquatic part > Subterranean stem = Root hair
 Phosphorus Aquatic part = Subterranean stem > Root hair
 N/P Root hair > Aquatic part > Subterranean stem

3. Seasonal variation of dry weight of *zostera*

The dry weight in the aquatic part and in the subterranean part of *Zostera* was estimated in the following stage of the life-cycle of *Zostera*.

July, 9 Maximum growth stage
 August, 22 Withering and decomposing stage
 October, 3 After outflowing of dead *Zostera*

TABLE 32

Seasonal variation of nitrogen and phosphorus in the subterranean part of *Zostera*.

Variação estacional de nitrogênio e fósforo na parte subterrânea da *Zostera*.

Variation saisonnière de l'azote et du phosphore dans la partie souterraine des *Zostera*.

| Date | Fresh subterranean stem | | | Old subterranean stem | | | Root hair | | |
|---------|-------------------------|-------|-----|-----------------------|-------|-----|-----------|-------|------|
| | N% | N/P | P% | N% | P% | N/P | P% | N% | N/P |
| 1956 | | | | | | | | | |
| Apr. 19 | 0.629 | 0.227 | 2.8 | | | | 0.876 | 0.119 | 7.4 |
| May 21 | 0.530 | 0.214 | 2.5 | | | | 0.906 | 0.136 | 6.7 |
| June 19 | 0.591 | 0.265 | 2.2 | | | | 0.979 | 0.137 | 7.1 |
| July 9 | 0.991 | 0.345 | 2.9 | 0.839 | 0.099 | 8.5 | 1.09 | 0.122 | 8.9 |
| Aug. 22 | 1.05 | 0.338 | 3.1 | 0.851 | 0.103 | 8.3 | 1.03 | 0.095 | 10.8 |
| Oct. 3 | 1.24 | 0.339 | 3.6 | 0.868 | 0.102 | 8.4 | 1.32 | 0.128 | 10.3 |
| Dec. 20 | 1.63 | 0.318 | 5.1 | 1.02 | 0.112 | 9.1 | 1.26 | 0.126 | 10.0 |
| 1957 | | | | | | | | | |
| Mar. 20 | 1.11 | 0.232 | 4.8 | 0.860 | 0.105 | 8.2 | 1.13 | 0.136 | 8.3 |
| May 22 | 0.649 | 0.226 | 2.9 | 0.826 | 0.094 | 8.8 | 1.24 | 0.133 | 9.3 |

| | | |
|--------------|-------|-------------------------------|
| December, 20 | | Stage of new sprout emergence |
| March, 18 | | Early growing stage |
| May, 22 | | Rapid growing stage |

Aquatic and subterranean parts of *Zostera* were collected from an area divided by a frame 1 m². After collection, the aquatic part was separated from the subterranean part at the highest node, the subterranean part was further separated into stem and root hair fractions. Thereafter, the stem was separated into two parts, namely, the new stem which was actively growing, and the old stem which was not. Each of these parts was dried and weighed separately.

Zostera fragments such dead leaves, stems and root hairs, were collected by the Ekman-Birge Bottom Sampler. Results are shown in Table 33.

The annual variation of the aquatic part was rather large as compared with that of the subterranean part. The weight of the aquatic part from July (maximum) to December (minimum) was 270g, while, that of the subterranean part was only 81g or 30 per cent of the former. On the other hand, the difference in number of plants per m² was small. In the period from July to August, the number of plant per unit area (m²) showed little difference, but the weight of the aquatic part decreased to one-half. This is due to the outflowing of the dead leaves, while the aquatic stem remained in place during the withering stage. This is true throughout the entire decomposition stage (from August to October). The plant number per unit area in December increased slightly, but its weight decreased because young leaves began to appear about November. Accordingly, throughout a year, the number of plants per m² in this area is relatively constant at about one hundred, but the weight per unit area varies greatly.

On the subterranean part, while, highest values of the subterranean part were found in May and July, and lowest values in October and December, with intermediate values in August and March. The weight increased rapidly from December to March and decreased rapidly from July to August. This may due to not only to their rapid decomposition or collecting error, but also to the outflowing of a part of the subterranean stem.

The lowest values of the new subterranean stem were found in December and March and the highest values in May, although the annual variation was small. The old subterranean stem showed higher values from May to August and rather lower values from October to March. The values for the new root hair part increased from the low values in October and December to the highest values in July. The weight of the *Zostera* fragments varied from 290 to 480 g/m², corresponding to 2.5 times of the subterranean part, and its seasonal variation was irregular. From May to August the weight of the aquatic part was higher than that of the subterranean part, its ratio being 100 to

46.5 — 83.6. From October to March the inverse was true the ratio being 100 to 130 — 185.

Dry weight of *Zostera* per unit area (m^2) (both aquatic and subterranean) in this bay was about the same as reported for Ikawazu Bay by Arasaki (1950).

C. Chemical Characteristics of Sea Water and Sediments in *Zostera* Area

1. Seasonal variation of sea water characteristics. (Fig. 43)

a. Chlorinity and silicate-Si

Seasonal variation of chlorinity and silicate-Si showed an inverse relationship. High silicate-Si and low chlorinity were found in the rainy season. Chlorinity above than $17^{\circ}/_{00}$ was found from September to April, the highest value being over $18^{\circ}/_{00}$. From May to August chlorinity sometimes dropped below $15^{\circ}/_{00}$.

The values of silicate-Si were about 1,500 γ/L in summer and autumn, and about 300 γ/L in winter (from January to March).

b. Oxygen saturation

Seasonal variation of oxygen saturation was in good agreement with the life-cycle of *Zostera marina*.

Supersaturation of oxygen (over 150%) was found in May, during the period of rapid growth of *Zostera*. On the other hand, the minimum oxygen saturation (below 50%) was found in August, during the period of withering and decomposition of *Zostera*.

c. pH

There is a good agreement in the seasonal variation between O_2 and pH. Highest values of pH (above 9.0) were obtained in May, and lowest values (below 8.0) in August. These maximum and minimum values were greatly different from those in the area lacking *Zostera*.

d. Phosphate-P

The highest values of phosphate-P were found from the end of June to the beginning of September. Judging from the low values of oxygen saturation and pH in those months, the high concentrations of phosphate-P may due to decomposition of dead *Zostera*. The lowest values of phosphate-P were obtained from January to May, corresponding to the rapid growth stage of *Zostera*.

e. Ammonia-N

Ammonia-N varied in much the same manner as phosphat-P,

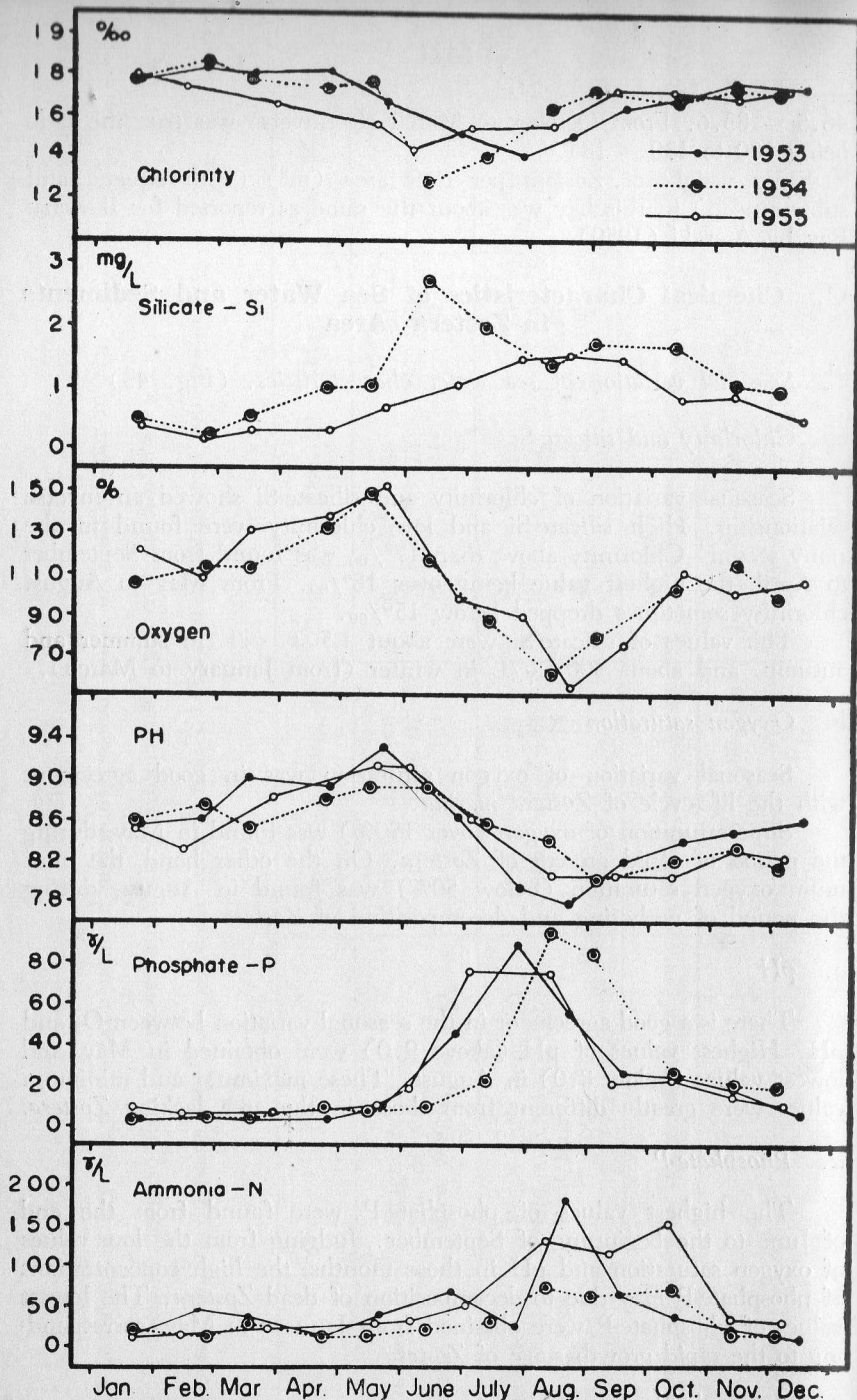


Fig. 43 — Seasonal variation of chemical character of sea water in the *Zostera* area
 Variação estacional das propriedades químicas da água do mar na área da *Zostera*
 Variation saisonnière des caractères chimiques de l'eau de mer dans la zone des *Zostera*

TABLE 34
Diurnal variation of chemical properties of sea water in the rapid growing stage of *Zostera*
Variação diurna das propriedades químicas da água do mar na fase de rápido crescimento da *Zostera*
Variation diurne des propriétés chimiques de l'eau de mer durant la croissance rapide du *Zostera*

| Observed time | Depth in m | Water temp. °C | Cl ‰ | pH | O ₂ cc/L | % | PO ₄ γ /L | NH ₃ -N γ /L | NO ₂ -N γ /L | NO ₃ -N γ /L | Remarks |
|------------------|---------------|----------------------|---------|------|------------------------|------|-------------------------|----------------------------|----------------------------|----------------------------|-----------|
| 9 p.m. | 0 | 21.4 | 16.53 | 9.0 | 8.47 | 157 | 19 | 40 | 0 | 4 | Clear sun |
| | 0.2 | | | 8.95 | | | | | | | |
| | 0.5 | | | 8.5 | | | | | | | |
| | 0.8 | | | 8.6 | | | | | | | |
| | 1.1 | 20.2 | 16.49 | 8.6 | 5.76 | 105 | 20 | 50 | | 15 | |
| 9 p.m. | 0 | 21.6 | 16.53 | 9.1 | 8.51 | 158 | | | | | Clear sun |
| | 0.2 | 21.6 | 16.51 | 9.05 | 8.31 | 154 | | | | | |
| | 0.3 | 20.8 | 16.45 | 8.9 | 7.04 | 129 | | | | | |
| | 0.7 | 20.7 | 16.47 | 8.7 | 6.42 | 117 | | | | | |
| | 0.9 | 20.3 | 16.46 | 8.6 | 5.95 | 103 | | | | | |
| 9 p.m. | 0 | 21.9 | 16.57 | 9.2 | 9.63 | 108 | | | | | Hazy sun |
| | 0.9 | 20.6 | 16.50 | 8.65 | 6.06 | 111 | | | | | |
| 8 p.m. | 0 | 20.5 | 16.55 | 8.9 | 7.75 | 141 | 16 | 40 | 0 | | |
| | 0.2 | 20.6 | 16.53 | 8.85 | 7.59 | 139 | | | | | |
| | 0.3 | | | | | | | | | | |
| | 0.5 | 20.5 | 16.53 | 8.75 | 7.44 | 126 | 16 | 40 | 0 | 10 | |
| 8 p.m. | | 20.5 | 16.63 | 8.7 | 7.08 | 129 | 21 | 40 | 0 | 15 | |
| 8 p.m. | 0 | 20.0 | 16.62 | 8.8 | 7.19 | 130 | | | | | |
| | 1.5 | 20.0 | 16.62 | 8.7 | 7.09 | 127 | | | | | |
| 10 p.m. | 0.5 | 19.8 | 16.62 | 8.7 | 6.75 | 122 | | | | | |
| | 0 | 19.8 | 16.61 | 8.65 | 6.58 | 119 | | | | | |
| 11 a.m. | 0 | 20.0 | 16.60 | 8.7 | 6.64 | 120 | 18 | 40 | 0 | 4 | |
| | 0.7 | 20.0 | 16.60 | 8.7 | 6.61 | 120 | 15 | 50 | 0 | 5 | |
| | 1.4 | 19.8 | 16.60 | 8.65 | 6.17 | 111 | 15 | 50 | 0 | 1.5 | |
| 11 a.m. | 0 | 20.0 | 16.56 | 8.7 | 6.55 | 118 | | | | | |
| | 1.2 | 19.8 | 16.55 | 8.6 | 5.84 | 105 | | | | | |
| 11 a.m. | 0 | 19.8 | 16.54 | 8.7 | 6.14 | 111 | | | | | |
| | 0.6 | 20.0 | 16.53 | 8.65 | 6.09 | 110 | | | | | |
| | 1.2 | 19.8 | 16.51 | 8.65 | 5.85 | 105 | | | | | |
| 8 a.m. | 0 | 19.8 | 16.53 | 8.7 | 6.19 | 112 | 17 | 50 | 0 | 4 | Cloudy |
| | 1.3 | 19.5 | 16.52 | 8.65 | 5.26 | 94.3 | 15 | 45 | 0 | 15 | |
| 8 a.m. | 0 | 19.8 | 16.56 | 8.7 | 6.17 | 111 | | | | | Hazy sun |
| | 1.4 | 19.5 | 16.58 | 8.6 | 5.36 | 96.1 | | | | | |
| 10 a.m. | 0 | 20.6 | 16.57 | 8.9 | 8.10 | 148 | | | | | Clear sun |
| | 0.2 | | | 8.85 | | | | | | | |
| | 0.3 | | | 8.8 | | | | | | | |
| | 0.5 | 20.4 | 16.57 | 8.8 | 7.40 | 135 | | | | | |
| | 1.4 | 19.8 | 16.56 | 8.6 | 5.66 | 102 | | | | | |
| 8 p.m. | 0 | 22.6 | 16.57 | 9.1 | 8.40 | 158 | 17 | 40 | 0 | 10 | Clear sun |
| | 0.3 | 21.9 | 16.53 | 8.9 | 8.81 | 164 | 17 | 40 | 0 | 5 | |
| | 0.5 | 21.4 | 16.49 | 8.8 | 8.30 | 151 | 17 | 40 | 0 | 15 | |
| | 0.8 | 20.8 | 16.48 | 8.75 | 7.04 | 129 | 14 | 40 | 0 | 10 | |
| | 1.1 | 20.7 | 16.49 | 8.7 | 6.39 | 117 | 15 | 50 | 0 | 1.5 | |

except that the maximum value of ammonia-N occurred about one month later than that of phosphate-P. This may be because phosphate-P was released more rapidly than ammonia-N while the *Zostera* was decomposing.

2. Diurnal variation of characteristics of sea water in the rapid growth stage of *zostera*

As above mentioned, several elements of sea water in *Zostera* zone showed a characteristic seasonal variation. The seasonal variation of oxygen and pH especially reflected the life-cycle of *Zostera*.

In the maximum growth stage, the dry weight of the aquatic part of *Zostera* was about 300 g/m², and total volume about 4,500 ml/m². Since the proportion of *Zostera* in shallow water (about 1-2m in depth) is so high, it naturally follows that the life-cycle of *Zostera* influences the characteristics of sea water in the *Zostera* zone. Accordingly, an observation on diurnal variation of sea water properties was made during the most growing stage of *Zostera*.

The 24 hours observation was made for starting at noon of June 1st of 1956. Sea water samples were collected every other hour from several depths at the same position. Tamura's syphon water sampler was used for water collection at each depth except the surface.

The sky was mostly clear and the water calm during the observation. (Table 34).

The diurnal variations of oxygen content and pH were great, although those of water temperature, chlorinity and soluble nutrient elements were very small.

a. Vertical distribution of oxygen and pH, and their diurnal variations (Fig. 44)

There is close relation in the diurnal vertical variations between the oxygen content and pH. The diurnal variations of oxygen and pH in surface water and in bottom water were as follows:

| | | pH | | | O ₂ | | Diff |
|---------|-------|------|------|-------|----------------|------|------|
| | | Max. | Min. | Diff. | Max. | Min. | |
| Surface | water | 9.2 | 8.7 | 0.5 | 9.63 | 6.14 | 3.49 |
| Bottom | water | 8.7 | 8.6 | 0.1 | 7.08 | 5.26 | 1.82 |

There was a great difference in the diurnal variation of the two in surface water as compared with bottom water.

The maximum value of oxygen was found at 16 o'clock in the surface water and at 18 o'clock in bottom water, while, the minimum value occurred from 4 to 8 o'clock at the surface and at 6 o'clock at the bottom. It is interesting that maximum and minimum values of oxygen were recorded at different times at the surface and at the

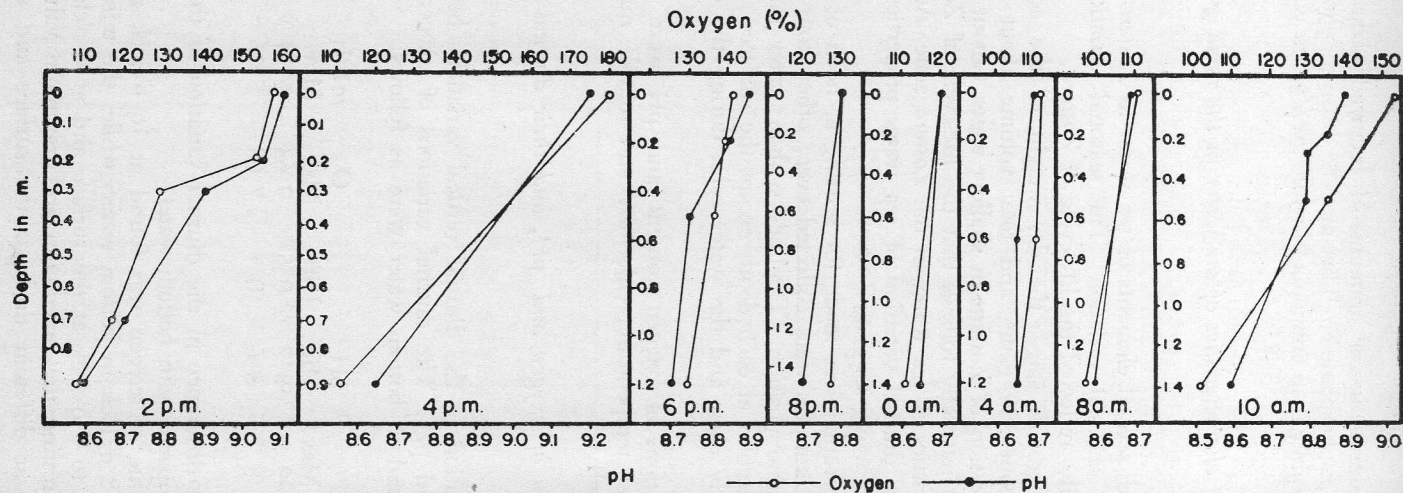


Fig. 44 — Diurnal variation of vertical distribution of pH and oxygen saturation %

Variação diurna da distribuição vertical do pH e saturação de oxigênio %

Variation diurne de la distribution verticale du pH et de la saturation en oxygène %

bottom. This was also true of pH, but the difference was not as marked with oxygen.

In the vertical distributions of oxygen and pH, a remarkably high values were obtained at surface, but tended to decrease from the surface to the bottom. The vertical difference of oxygen and pH between surface water and bottom water was highest in day time, and began to decrease after the sun set. These vertical differences were very small from midnight to sun rise. After 10 o'clock, they increased rapidly in the surface water.

b. Diurnal variation of oxygen in water column (1 m₂)

The oxygen content in the water column (1m²) was calculated from the above data. Fig. 45 shows the oxygen content per unit vo-

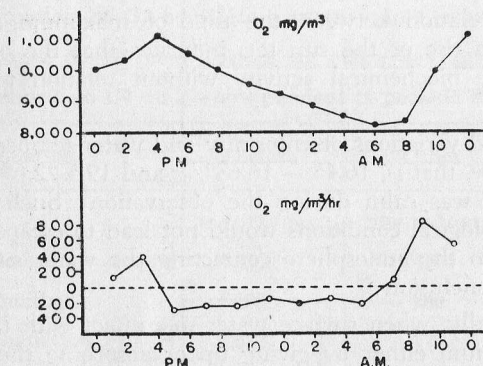


Fig. 45 — Diurnal variation of dissolved oxygen in the water column (m²)
 Variação diurna do oxigênio dissolvido na coluna d'água (m²)
 Variation diurne de l'oxygene dissous dans une colonne d'eau (m²)

lume (mg/m³) and the variation of oxygen every 2 hours for comparison. The results in Fig. 45 indicate a maximum value of O₂ at 16 o'clock and minimum at 6 o'clock. The maximum value of O₂ occurred a little before sun set. On the other hand, the minimum value of O₂ was found after sun rise. The O₂ value showed a gradual decrease from 16 o'clock to 6 o'clock, and a gradual increase from about 7 o'clock to 16 o'clock.

It was interesting that the rate of decrease of O₂ was rather constant from 16 o'clock to 6 o'clock. This will be discussed further later on.

c. Factors affecting for diurnal variation of oxygen

Two factors are concerned in the diurnal variation of oxygen, namely; (1) the biochemical factor including photosynthesis, respira-

tion of plants, and oxidation of organic matter and inorganic matter, and (2) the physical factor including giving up or absorbing oxygen to reach equilibrium with the atmosphere, water mass movement, and eddy diffusion.

Nagai (1955) concluded that the escape of supersaturated oxygen into the atmosphere in contact with water occurs when the solubility of oxygen changes because of variations of temperature and salinity.

Sugiura (1954) concluded that when the diurnal variation of oxygen is controlled mainly by the biochemical activity without relation to the physical factors, the maximum O_2 occurs about one or two hours before sun set, and the minimum O_2 one or two after sun rise. On the other hand, when diurnal variation of O_2 is controlled only by physical factors, or by both, the above phenomenon is not true.

Regarding diurnal variation of O_2 in this *Zostera* zone, the following points are noted about its controlling factors.

(1) The relation between the time of maximum and minimum O_2 and the sun rise or the sun set, indicates that the oxygen content is controlled by biochemical activity without relation to the physical factors.

(2) Diurnal variations of chlorinity and water temperature were remarkably narrow, that is, 16.45 – 16.63‰ and 19.5–22.6°C respectively. Furthermore, it was calm during the observation. Such oceanographical and meteorological conditions would not lead to escape of the supersaturated O_2 into the atmosphere contacting the water surface, judging from Nagai's conclusion.

(3) Generally, when surface water in contact with the atmosphere reaches equilibrium either by giving up or absorbing the oxygen until the water is just saturated, the rate of reaching equilibrium of oxygen will be controlled by the difference between oxygen partial pressure in the atmosphere and oxygen tension in the surface water. In the observation, supposing that the supersaturated oxygen (during the day time) escaped into the atmosphere from sun set to sun rise, the rate of decrease of oxygen should be fast at first and become slower and slower. Nevertheless, in this observation the rate of decrease of oxygen showed almost a constant value from sun set to sun rise. On the other hand, the rate of respiration of plants shows a relatively constant value at same temperature. Accordingly, we can conclude that the decrease of oxygen from sun set to sun rise was caused mainly by the respiration of *Zostera*.

(4) The density of *Zostera* in the observed area was rather high, namely, about one hundred plants, and with about 300g of dry matter in the aquatic part and about 4.5 L of volume per m^2 respectively.

For these reasons, we feel that the diurnal variation of oxygen is mainly affected by the biochemical activity of *Zostera*, and that the effect of physical factors is rather small in comparison with biochemical activity.

3. Assumption of the production of *Zostera* during the rapid growing stage.

a. Estimation of the diurnal production (Table 35 and 36)

As described in the previous section, the diurnal variation of oxygen was affected chiefly by biochemical factors.

The diurnal production of *Zostera* was estimated from the results of the diurnal variation of dissolved oxygen in the *Zostera* area. In this estimation, two assumptions were made as follows: (1) photosynthesis was entirely stopped from sun set to sun rise, (2) respiration rate was constant during both night and day.

T A B L E 3 5

Diurnal production of O_2 by *Zostera* in the rapid growing stage.

Produção diurna de O_2 pela *Zostera* na etapa de rápido crescimento.

Production diurne en O_2 du *Zostera* pendant la période de croissance rapide.

| Production | <i>Zostera</i> | Other | Total |
|------------------|------------------------|------------------------|------------------------|
| | mg/m ³ /day | mg/m ³ /day | mg/m ³ /day |
| Respiration | 4,350 | 450 | 4,800 |
| Net production | 1,280 | — 280 | 1,000 |
| Gross production | 5,630 | 170 | 5,800 |

T A B L E 3 6

Efficiency of energy production by *Zostera* in water column (1.3 meters deep).

Eficiência da produção de energia pela *Zostera* na coluna da água, (1,3 metros profundidade).

Efficacité de la production énergétique par les *Zostera* dans une colonne d'eau (1,3 mètre de profondeur).

| Production | O_2 /m ² /day | C/m ² /day | Energy efficiency |
|------------------|----------------------------|-----------------------|-------------------|
| Respiration | 5,700mg | 2,100mg | 0.41% |
| Gross production | 1,600 | 600 | 0.13 |
| Net production | 7,300 | 2,700 | 0.60 |

Gross production of oxygen by *Zostera* in the water column per unit area (m^2) was high in comparison with that of phytoplankton in the non *Zostera* area (chapter IV). This may be due to a difference of density of cells containing chlorophyll.

The respiration was high compared with the net production. This may be because the growth rate of *Zostera* had been decreased at the time of the observation which corresponded to the end of the growing stage.

In order to know the production of organisms in the water other than *Zostera*, the method described in chapter VI was used. The production of phytoplankton in the *Zostera* area was small in comparison with the *Zostera* production or the production of phytoplankton in non-*Zostera* zone. This may be because the vast amount of *Zostera* obstructed the photosynthesis of phytoplankton.

b. Productive efficiency of *Zostera* from the solar radiation energy

As the solar radiation energy was not determined directly by the author, the observations of Ishinomaki Meteorological Station were used. The solar radiation energy from noon of 1st to noon of 2nd June was 424 cal/m^2 . The efficiency of the gross production was 0.60% and 0.13% in the net production. These values were remarkably high compared with these values for phytoplankton in the non-*Zostera* area.

4. Seasonal variation of properties of sediments

In Fig. 46, the results in 1953 and 1954 show the soluble ammonia-N and phosphate-P in sediments and those in 1955 and 1956 show soluble ammonia-N and phosphate-P in interstitial water of sediments. Contents of nitrite-N and Nitrate-N were not shown because of their very low content. These elements in sediments were determined from the surface to a depth of 10 cm and the values in the Fig. 46 are mean values.

a. Nitrogen

Ammonia-N was low from January until the end of July when it rose sharply reaching a peak in October followed by a gradual decrease until January.

Relatively high values of total-N occurred from June to January with the lowest values from March to June.

b. Phosphorus

The seasonal variations of phosphate-P and total-P agreed relatively well with those of ammonia-N and total-N. Such seasonal variations of nitrogen and phosphorus reflect the life-cycle of *Zostera*. The months

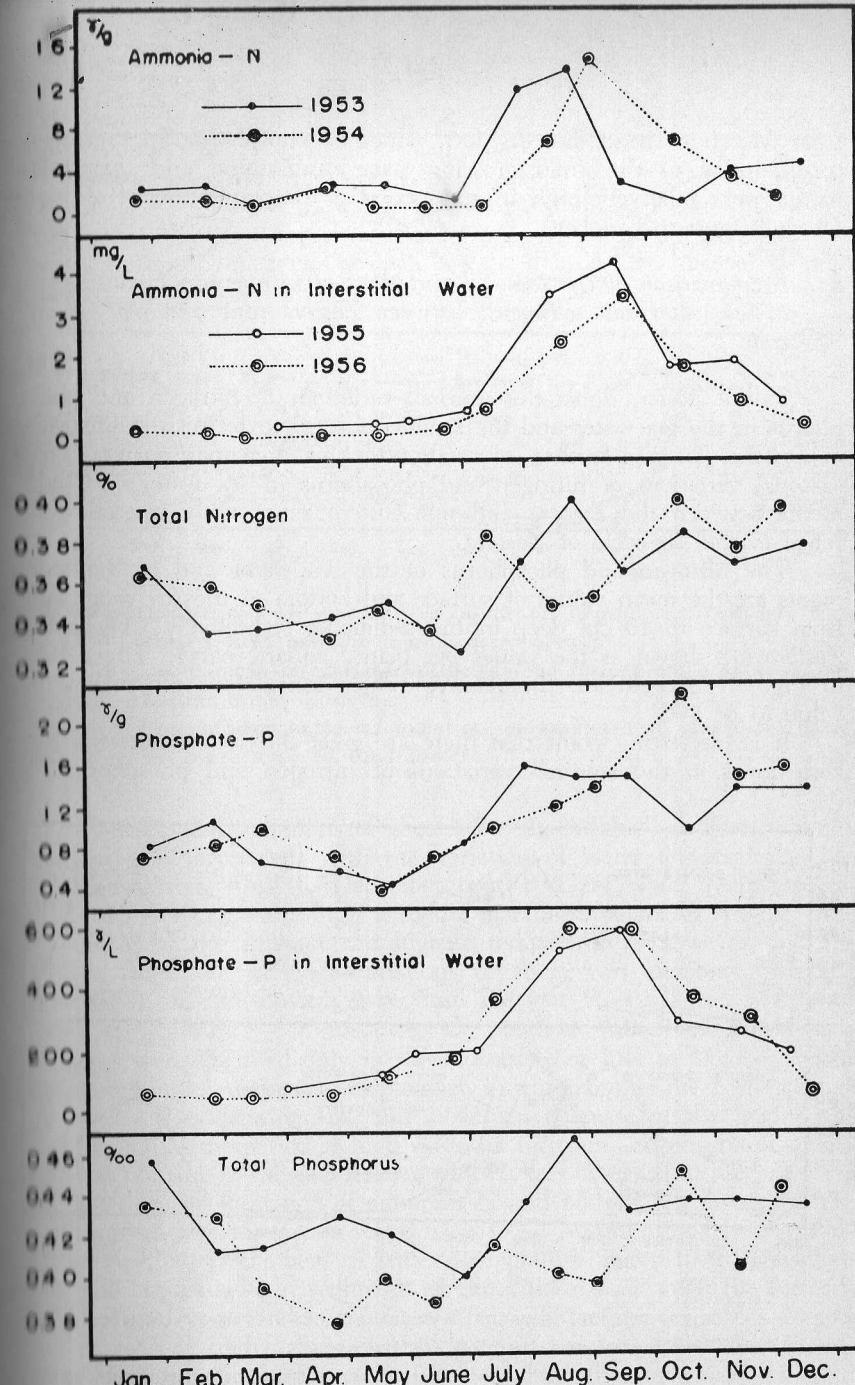


Fig. 46 — Seasonal variation of nitrogen and phosphorus in sediments in the *Zostera* area.
Variação estacional de nitrogênio e fósforo nos sedimentos na área da *Zostera*.
Variation saisonnière l'azote et du phosphore dans les sédiments de la zone des *Zostera*.

from March to June showing low values of phosphorus and nitrogen corresponded to the rapid growing stage of *Zostera*, and these elements were relatively high in the period of decomposition of *Zostera* (from August to October).

5. A comparison of the seasonal variations of nitrogen and phosphorus in sea water and sediments between *Zostera* zone and non-*Zostera* zone.

In the *Zostera* zone, the seasonal variations of nitrogen and phosphorus in the sea water and the sediments seem to reflect the life-cycle of *Zostera*. To gain further information on this, a comparison was made seasonal variations of nitrogen and phosphorus in sea water and sediments between the *Zostera* and non-*Zostera* zones with especial reference to the life-cycle of *Zostera*.

The nitrogen and phosphorus of the sea water and of the sediments are the mean values of surface and bottom in the sea water and from surface to 10 cm deep in the sediments respectively. Those for *Zostera* are shown as the values per plant (aquatic part). The values in Fig. 47 and 48 are the relative values considering the maximum value to be 100.

It is interesting point that there are great differences between the both zones in the seasonal variations of nitrogen and phosphorus.

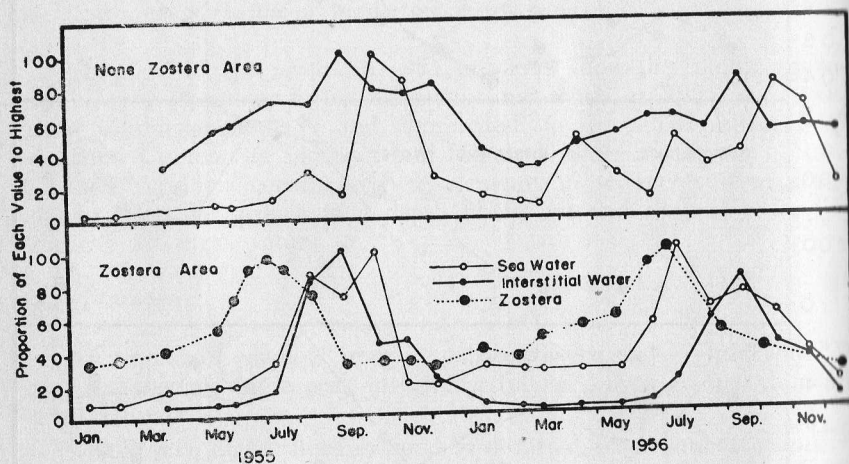


Fig 47 — Comparison of seasonal variation of nitrogen between the *Zostera* área and the non *Zostera* area
 Comparação da variação estacional de nitrogênio entre as áreas de *Zostera* e não *Zostera*
 Comparaison entre les variations saisonnières de l'azote dans les zones avec ou sans *Zostera*

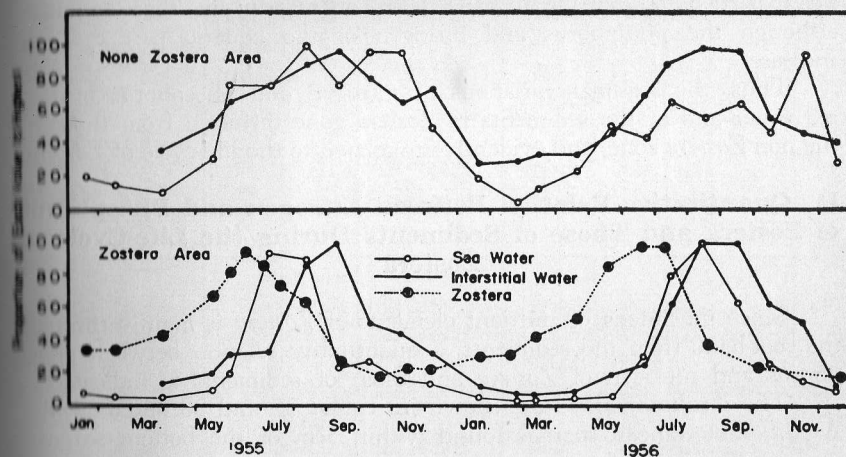


Fig. 48 — Comparison of seasonal variation of phosphorus between the *Zostera* area and the non- *Zostera* area
 Comparação da variação estacional de fósforo entre as áreas de *Zostera* e não *Zostera*
 Comparaison entre les variations saisonnières du phosphore dans les zones avec ou sans *Zostera*

The seasonal variations of these elements in the non-*Zostera* zone were in good agreement with the variation of water temperature. In the season from April to December over 10°C of water temperature, these two elements were high with the maximum values in August and September at the time of the highest temperature. However, in the *Zostera* zone, the seasonal variations of these two elements differed from those in non *Zostera* zone, and did not always agree with the water temperature. For instance, the highest values of these two elements were obtained only in the months from July to October, with the maximum in August and September. Furthermore, in the *Zostera* zone there was a sudden increase and a sudden decrease at the beginning and the end of the period of high values of nitrogen and phosphorus, but this was not true in the non-*Zostera* zone. It was observed in the previous chapter that the formation of ammonia-N and phosphate-P in sediments was rapid at the temperature above 10 or 15°C. Accordingly, in the season (from April to December) of water temperature above 10°C, phosphate-P and ammonia-N in sediments of the *Zostera* zone might be formed at the same rate as in the non *Zostera* zone. Therefore, the difference of the months of high values of these elements between the two zones, should be related to the life-cycle of *Zostera*. Namely, the low values from April to June correspond to the growing stage of *Zostera*, as indicated by the increase of these elements in *Zostera*. Similarly, November and December correspond to the new sprout emergence stage. The subterra-

nean part of *Zostera* may have been organically in these months, although the phosphorus and nitrogen of the aquatic part did not increase.

Thus, the seasonal variations of nitrogen and phosphorus of the sea water and of the sediments in *Zostera* zone differed from those in the non *Zostera* zone, and evidently are related to the life-cycle of *Zostera*.

D. Quantitative Relation Between Nitrogen and Phosphorus of *Zostera* and Those of Sediments During the Life-Cycle of *Zostera*

Since the intake of nutrient elements of *Zostera* is mainly through the root-hairs from the sediments, a quantitative relation between phosphorus and nitrogen of *Zostera* and those of sediments is indicated.

The results obtained are shown in Tables 37 and 38 and Fig. 49. As the subterranean stem is found within 5cm of the bottom surface,

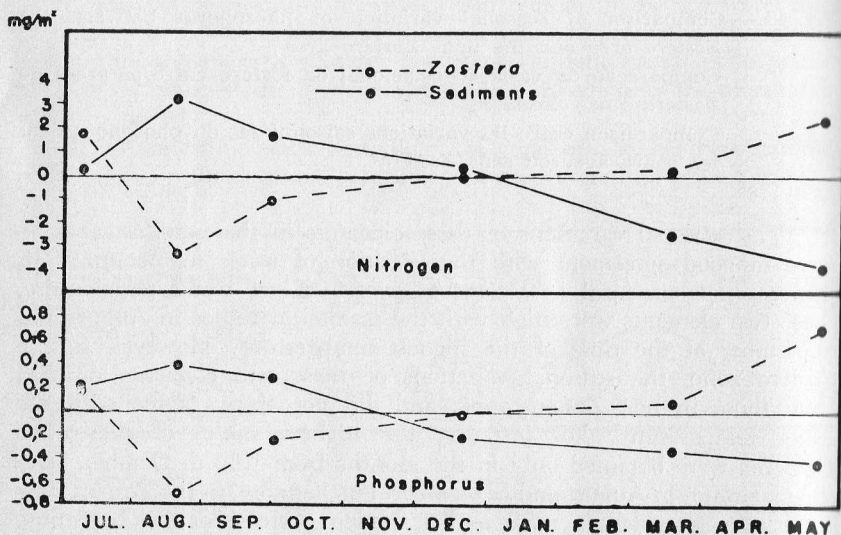


Fig. 49 — Quantitative relation in variations of nitrogen content and phosphorus content between sediments and *Zostera*

Relação quantitativa das variações de nitrogênio e fósforo entre sedimentos e *Zostera*

Relation quantitative dans les variations de la teneur en azote et en phosphore entre les sédiments et les *Zostera*.

the phosphorus and nitrogen contents of sediments were calculated per unit area (m^2) for this zone. However, as this zone contains fragments of *Zostera* and or the other detritus, the capacity of sediments was obtained by subtraction of the residual parts from the above capa-

TABLE 37

Quantitative relation between amounts of total nitrogen in *Zostera* and in sediments (per m²) during life-cycle of *Zostera*.

Relação quantitativo entre o nitrogenio total na *Zostera* e nos sedimentos (por m²) durante o ciclo vital da *Zostera*.
Relation quantitative entre les quantités d'azote total contenue dans les *Zostera* et dans les sédiments (par m²) durant le cycle vital du *Zostera*.

| Date | | July 9 | Aug. 22 | Oct. 3 | Dec. 20 | Mar. 18 | May 22 | Range |
|---------------------------------------|---|---------|---------|--------|---------|---------|--------|--------|
| Leaf and stem | | 5.18gr | 2.21gr | 1.38gr | 1.23gr | 1.42gr | 3.45gr | 3.95gr |
| Subter- ranean stem and root | Freh sub. stem | 0.35 | 0.25 | 0.30 | 0.31 | 0.22 | 0.29 | 0.13 |
| | Old sub. stem | 0.71 | 0.63 | 0.47 | 0.51 | 0.56 | 0.73 | 0.26 |
| | Root hair | 0.28 | 0.14 | 0.11 | 0.09 | 0.19 | 0.30 | 0.21 |
| | Total | 1.34 | 1.02 | 0.88 | 0.91 | 0.97 | 1.32 | 0.46 |
| Whole plant | Total | 6.52 | 3.23 | 2.26 | 2.14 | 2.39 | 4.77 | 4.38 |
| | Difference from the previous examination | + 1.75* | — 3.29 | — 0.97 | — 0.12 | + 0.25 | + 2.38 | |
| Bottom mud | Contents in mud * | 69.7 | 71.2 | 72.9 | 74.4 | 71.3 | 66.6 | 7.8 |
| | Fragments of <i>Zostera</i> | 4.1 | 6.3 | 6.4 | 5.3 | 6.0 | 6.9 | 2.8 |
| | Total | 73.8 | 77.5 | 79.3 | 79.7 | 77.3 | 73.5 | 6.2 |
| | Difference from the previous value | + 0.3* | + 3.7 | + 1.8 | + 0.4 | — 2.4 | — 3.8 | |

(*) Difference from the value of May (22)

TABLE 38

Quantitative relation between phosphorus in *Zostera* and in the sediments (per m²) during the life-cycle of *Zostera*.
 Relação quantitativa entre o fósforo na *Zostera* e nos sedimentos (por m²), durante o ciclo vital da *Zostera*.
 Relation quantitative entre le phosphore contenu dans les *Zostera* et dans les sédiments (par m²) durant le cycle vital du *Zostera*.

| Leaf and stem | | July 9 | Aug. 22 | Oct. 3 | Dec. 20 | Mar. 18 | May 22 | Range |
|--------------------------------------|---|---------|---------|--------|---------|---------|--------------|--------|
| Date | | 1.01gr | 0.40gr | 0.20gr | 0.21gr | 0.28gr | 0.86gr | 0.81gr |
| Subter- anean stem and root | Fresh sub. stem | 0.12 | 0.081 | 0.031 | 0.060 | 0.046 | 0.10 | 0.074 |
| | Old sub. stem | 0.084 | 0.076 | 0.056 | 0.056 | 0.068 | 0.083 | 0.028 |
| | Root hair | 0.032 | 0.013 | 0.010 | 0.009 | 0.023 | 0.032 | 0.023 |
| | Total | 0.236 | 0.170 | 0.147 | 0.125 | 0.137 | 0.215 | 0.111 |
| Whole plant | Total | 1.25 | 0.57 | 0.35 | 0.34 | 0.42 | 1.08 | 0.91 |
| | Difference from the previous examination | + 0.17* | — 0.68 | — 0.22 | — 0.01 | + 0.08 | + 0.66 | |
| Bottom mud | Contents in mud | 9.7 | 9.9 | 10.2 | 10.1 | 9.7 | | 0.9 |
| | Fragment of <i>Zostera</i> | 0.33 | 0.50 | 0.51 | 0.42 | 0.47 | 9.3 | 0.21 |
| | Total | 10.0 | 10.4 | 10.7 | 10.5 | 10.2 | 0.54 | 0.9 |
| | Difference from the previous examination | + 0.2* | + 0.4 | + 0.3 | — 0.2 | — 0.3 | 9.8 — 0.4 | |

(*) Difference from the value of May (22)

city after such residual parts were separated through a sieve with an opening of 1 mm.

Furthermore, as these fragments of *Zostera* play an important rôle on the circulation of nitrogen and, phosphorus through their decomposition, the amounts of these elements in the fragments of *Zostera* were estimated also.

While amount of benthonic algae and benthonic animals must be considered, these values were omitted from this discussion because of their small amounts.

These elements in the aquatic part showed minimum values in December (nitrogen) and in October (phosphorus), and maximum values in July (both elements). As to nitrogen and phosphorus in the subterranean part, the minimum values of the new subterranean stem were obtained in March (both elements), those of the root-hairs in December (both elements), and the maximum values of both fractions were found in May and in July. On the whole subterranean parts, the minimum values were obtained in October (nitrogen) and in December (phosphorus), and the maximum values in July (both elements). This was true for the total amounts of the aquatic part and the subterranean part.

Both elements in the subterranean stem showed very low values in March in contrast to the root hairs. This may be attributable to the movement of these elements from stem to the leaves, judging from the remarkably low content (%) of these elements in March in comparison with those in December, even though the dry weight was about the same in the two months.

Generally speaking, the amounts of these two elements and their variation were quite small from October to March, and this period can be called as "a resting stage".

In this discussion, the amounts of nitrogen and phosphorus in sediments included the amounts in fragments of *Zostera*. On contrast with the amount of nitrogen and phosphorus in *Zostera*, those in sediments showed the maximum values in October and in December, and the minimum values in May.

Annual variations of these elements in *Zostera* were about 4.5 $\mu\text{g}/\text{m}^2$ of N (about 4 g/m^2 in the aquatic part and about 0.5 $\mu\text{g}/\text{m}^2$ in subterranean part) and about 0.9 g/m^2 of P (about 0.8 $\mu\text{g}/\text{m}^2$ in the aquatic part and 0.1 g/m^2 in the subterranean part). The annual variations of these elements in the aquatic part were more than 8 times those in subterranean part.

On the other hand, annual variations of these elements in sediments were about 6.2 g/m^2 of N and about 0.9 g/m^2 of P. These annual variations in sediments and *Zostera* were nearly equal.

Fig. 49 shows the quantitative relation between seasonal variations of nitrogen and phosphorus in sediments and those in *Zostera* (total amounts of aquatic part and of subterranean part). The increase and decrease in seasonal variations of these elements showed

an inverse correlation between *Zostera* and the sediments. Furthermore, the balance of increase and decrease was rather similar quantitatively between *Zostera* and sediments. This indicates that *Zostera* takes in much nitrogen and phosphorus from the sediments during its period of active growth.

Summary

In this chapter, the circulation of nutrient elements of sea water and sediments in *Zostera* area was examined in relation to the life-cycle of *Zostera*. The results are summarized as follows.

1). The life-cycle of *Zostera*: New sprouts begin to emerge in October or November and elongate gradually until March. In March, the height of *Zostera* is about 60 cm. The rapid growth starts about April and continues until about the end of June, when the height reaches about 200 cm. Shortly thereafter most of them die and are carried out of the area by currents.

2). Oxygen production by *Zostera* was estimated in the growing stage, and the productive efficiencies for the solar radiation energy were 0.6% in gross production, and 0.13% in net production.

3). Annual variation of dry weight of the aquatic part of *Zostera* per unit area (m^2) was much greater than that of the subterranean part, namely; 41-314 g/m^2 in the aquatic part and 76-157 g/m^2 in the subterranean part.

The annual variation of whole dry weight of *Zostera* (aquatic part and subterranean part) varied from 117-460 g/m^2 in proportion to that of the height.

4). The lowest values of nitrogen and phosphorus and the narrowest ratio between the two were found during the rapid growing stage, and their highest values were obtained in the resting stage.

Judging from the seasonal variation of the N/P ratio in the aquatic part, we conclude that : In the rapid growing stage, the rate of intake of phosphorus is more rapid than that of nitrogen. Also the rate of release of phosphorus in the decomposition stage is more rapid than that of nitrogen.

5). The nitrogen and phosphorus contents in the subterranean part were remarkably low in comparison with those in the aquatic part. The seasonal variations of these contents in the subterranean stem agreed rather well with those in the aquatic part, while, in the root hair these elements did not show great variations.

The seasonal variation of the ratio of nitrogen to phosphorus showed a similar tendency to that in the aquatic part.

6). The following relationships of N, P and N/P were found between the aquatic part, the subterranean stem and root hairs.

N Aquatic part > Subterranean stem = Root hair
P Aquatic part = Subterranean stem > Root hair

N/P Root hair > Aquatic part > Subterranean stem

7). Diurnal variation of pH and oxygen during the rapid growing stage was remarkably large reflecting the photosynthesis of *Zostera*. Their diurnal variations were 8.7-9.2 in pH and 5.26-9.63 ml/L of oxygen.

8). Seasonal variations of N and P in sea water and sediments in the *Zostera* area changed with relation to the life-cycle of *Zostera* and differed remarkably from those in the non-*Zostera* area. The difference was especially large during the rapid growing stage, and in the withering and decomposition stage.

9). There is an inverse correlation between the content of nitrogen and phosphorus in *Zostera* and the sediments with relation to the life-cycle of *Zostera*.

X. - AN OUTLINE OF BIOLOGICAL PRODUCTIVITY IN MATSUSHIMA BAY

In the previous chapters, several factors relating to the biological production in Matsushima Bay were examined. However, we have not sufficient informations to elucidate the synthetical characteristics of biological production in the bay.

In this chapter, a general view of the characteristics of the productivity in Matsushima Bay will be discussed through the quantity of biological production and the standing crop of several organisms and of nitrogen in sediments.

A. Solar Radiation Energy

The Sendai Meteorological Station summarized the solar radiation energy in Matsushima Bay as follows.

| | Per unit area (m^2) | Whole bay |
|-------------------|--|--|
| Yearly mean value | $3.6 \times 10^6 \text{ cal}/\text{m}^2/\text{day}$ | $1.44 \times 10^{14} \text{ cal}/\text{day}$ |
| For one year | $1.3 \times 10^9 \text{ cal}/\text{m}^2/\text{year}$ | $5.2 \times 10^{16} \text{ cal}/\text{year}$ |

(From September 1956 to August 1957)

B. Approximate Values of Production of Various Plants

1. Production of phytoplankton

The production of plankton in the bay was estimated on the basis of the results at the central part of Shiogama Harbor described in the previous chapter. The oxygen production per unit area (m^2) was 610 $\text{g}/\text{m}^2/\text{year}$ in gross and 400 $\text{g}/\text{m}^2/\text{year}$ in net production. The ne-

cessary energy for photosynthesis of plankton was calculated on the basis of glucose. The results are as follows.

Gross production

| | Per unit area (m ²) | Whole bay |
|-------------------|--|-------------------------------|
| Yearly mean value | 5.85×10^3 cal/m ² /day | 2.3×10^{11} cal/day |
| For one year | 2.1×10^6 cal/m ² /year | 8.4×10^{13} cal/year |

Net production

| | | |
|-------------------|--|-------------------------------|
| Yearly mean value | 3.81×10^3 cal/m ² /day | 1.4×10^{11} cal/day |
| For one year | 1.4×10^6 cal/m ² /year | 5.6×10^{13} cal/year |

The productive efficiency of phytoplankton for the solar radiation energy was 0.16% in gross and 0.11% in net production.

For 109 mg of oxygen released in photosynthesis, the phytoplankton will taken up 7.2 mg of nitrogen ⁽¹¹²⁾. At this rate the amount nitrogen produced annually was as follows:

| | Per unit area (m ²) | Whole bay |
|------------------|---------------------------------|-----------------|
| Gross production | 40.3 g/m ² /year | 1,610 tons/year |
| Net production | 26.4 " | 1,060 " " |

2. Production of *Zostera*

From the results in the chapter X, the net production of *Zostera* was estimated as follows:

| | Per unit area (m ²) | Whole bay |
|------------|---------------------------------|-----------------|
| Dry weight | 340 g/m ² /year | 10,200 ton/year |
| Nitrogen | 4.4 " | 132 " |

The net production in the whole bay was calculated on the assumption that the growing area of *Zostera* is 30 Km².

According to the author's results ⁽⁷⁵⁾ of analysis on crude protein, carbohydrate and crude fat in *Zostera*, the energy per unit weight (1g) of dry matter was calculated as 1,800 cal/g. From this values, the necessary energy for the above annual net production of *Zostera* was calculated to be 1.8×10^{13} cal/year. The productive efficiency was 0.046% for the solar radiation energy in the growing area of *Zostera*.

Although this value can not be compared directly with the efficiency of phytoplankton because the energy of phytoplankton was cal-

culated on the basis of glucose, it would be safe to say that net productive efficiency of *Zostera* is remarkably small in comparison with that of phytoplankton on an annual basis.

In the rapid growing stage of *Zostera*, however, the net productive efficiency of *Zostera* showed good agreement with that of phytoplankton. The dry matter of *Zostera* including subterranean part produced in the three months from April to June was 7,200 ton/30 Km², and the necessary energy for photosynthesis for producing this is 1.3×10^{13} cal.

On the other hand, as the solar radiation energy for these three months was 1.3×10^{16} cal per growing area (30Km²) of *Zostera*, the net productive efficiency is 0.1% for solar radiation energy. There is not a great difference between the net productive efficiency in the rapid growing stage and the efficiency (0.13%) calculated from the diurnal oxygen production by *Zostera* as mentioned earlier.

This net productive efficiency is close to that (0.11%) of phytoplankton.

3. Production of Laver, *Porphyra tenera* Kiellm

In Matsushima Bay, the Laver, *Porphyra tenera* Kiellm is cultured from autumn to early spring. The yield of the laver is affected by meteorological and oceanographical conditions and concentration of nutrient elements. According to the statistics of the Miyagi-Ken Fisheries Cooperative Association, the annual production of laver (dry matter completed) was $3.25-4.5 \times 10^7$ sheets through a 4 year period. On the basis of these data, the amount of nitrogen of laver per year and the net productive efficiency for the solar radiation energy were calculated.

If the weight of the laver is 2.5 g per sheet and its nitrogen content is 5% on the dry matter basis, the net production of laver in the whole bay was 81-113 tons containing 4.1-5.7 tons of nitrogen. The energy of the laver per gram (as dry matter) was 2,800 cal, calculated from the chemical composition.

The necessary energy for the net production of laver was $2.3 - 3.2 \times 10^{11}$ cal. The growth area of the laver in this bay is about 1Km² [corresponding to the area of the cultural equipment (Nori hibi)]. As the solar radiation energy in the cultural period (from November to March) was 4.6×10^{14} cal/ per cultural area for the five months, the net productive efficiency of the laver for solar radiation energy was 0.05 - 0.07%.

These values are very small in comparison with that of phytoplankton and of *Zostera* (annual average). However, it is noted that the net productive efficiency of phytoplankton in the same months was similar (about 0.05%).

4. Production of three principal plants in the bay

The total net production of the three principal plants (phyto-

plankton, *Zostera* and laver) amounted to about was 1,200 tons of nitrogen and 6.9×10^{13} cal of energy.

The productive efficiency was 0.15% for the entire annual solar radiation energy in the bay. The productive efficiency of *Zostera* in the rapid growing stage was closed to that of phytoplankton. Similarly, the efficiency of the cultured laver showed rather good agreement with that of phytoplankton in same period. Therefore, it appears that the water has an almost constant efficiency of primary production under the same environmental conditions.

C. Standing Crop of Plankton

The standing crop of nitrogen in Matsushima Bay was estimated from the results on the seasonal variation of nitrogen in the net plankton (including zooplankton.) Estimating the quantity of water in the bay corresponds to 9×10^7 m³, the amounts of nitrogen in the whole bay varies from 0.135 to 1.4 tons and average 0.57 ton.

D. Standing Crop and Net Production in Animals

1. Catch of fish

According to the Miyagi-ken Statistic & Investigation Office, 3,560 tons of fresh fish were caught in Matsushima Bay in 1957. If the moisture content of fresh fish and nitrogen content of dried fish are 70% and 7% respectively, the dry weight of the catch of fish was 1,070 tons and contained 75 tons of nitrogen.

On George Bank, Clark (1946) reported 0.00005 — 0.00025% as the efficiency for solar radiation energy for the fish catch. Hanaoka (1952) reported 0.0018% for this efficiency in Tokyo Bay

For comparison with these values, the author has calculated the efficiency of the catch of fish in Matsushima Bay. The energy of fish amounts to 2.6×10^{12} cal. Using 240 cal per gram of fresh fish in accordance with Clark's calculation, the efficiency for the solar radiation energy for the catch is 0.005%. This is remarkably high in comparison with Clark's and Hanaoka's values.

2. Catch of oysters

According to Miyagi-ken Fisheries Cooperative Association, the amount of cultural oysters was taken 1,640 tons in 1957.

It is said that the death rate of the adult cultured oyster from natural causes is remarkably low. If this is true then the catch of oysters corresponds approximately to the net production. Accordingly, the amount of nitrogen of oysters caught and the efficiency for the solar radiation energy for the catch were calculated to be 22 tons and 0.0027% respectively on the basis of the following figures.

| | |
|---|-------------|
| Moisture content of fresh oysters | 83% |
| Nitrogen content of dry oysters | 7% |
| Energy per one gram of dry meat of oyster | 5.000 cal/g |
| (calculated from the chemical composition of oysters) | |

3. Standing crop of benthonic animals

Distribution of the benthonic community in summer in this bay was reported by Yamamoto (1951), the seasonal succession of benthonic animals was reported by the author et al (1955, 1957). Generally speaking, there was a large difference between the benthonic community in the *Zostera* and non *Zostera* zones.

The gravimetric population of benthonic animals in the whole bay regardless of species was worked out from the results in the authors paper (1957). The dominant species in the *Zostera* zone was *Macoma incongrua*, and *Nereis* sp. in the non *Zostera* zone. The dry meat weight in the *Zostera* zone varied from 20 — 60 g/m² monthly and 4 — 20g/m² in the non *Zostera* zone. Annual dry weight of benthonic animals in the whole bay amounted to 640 — 2,000 ton. This was based on the assumption that the area of the *Zostera* zone in three times that of the non *Zostera* zone.

The calculated annual amount of nitrogen was 45 — 140 tons (average 90 tons), assuming a nitrogen content of 7% in the animals (without shell).

E. Existing Amount of Easily Decomposable Nitrogen in Sediments

The author's studies indicate that most of the organic matter is deposited on the bay bottom and is decomposed there. Lindeman reported (1941), that about 10% of the plants produced are utilized by herbivorous animals in the water. Consequently, the rest (about 90%) will be decomposed in the water or on the bottom after deposition.

As mentioned in chapter IX, in Matsushima Bay, the added organic nitrogen on the sea bottom amounts to 36.4g/m²/year. About 25,4 g/m²/year out of the annual added organic nitrogen will return into overlying sea water after decomposition.

These amounts in the whole bay amount to 1,090 tons/year of organic nitrogen deposited and 760 tons/year of organic nitrogen decomposed. Hence, it should be noted that the amount of organic nitrogen deposited is very close to the amount of nitrogen produced primarily.

Table 39 shows the existing amounts of total nitrogen and easily decomposable nitrogen in the sediments from bottom surface to a depth of 5cm. The values for nitrogen in sediments were estimated on the parts passed through a sieve with an opening of one mm. in a wet state. Easily decomposable nitrogen content was obtained by same method as mentioned in chapter IX.

Figures in Table 38 show that easily decomposable nitrogen corresponds to about 10% of total nitrogen. The total nitrogen of the *Zostera* area included that of the fragments of *Zostera*, because the latter may play an important rôle in the decomposition.

TABLE 39

Existing amount of nitrogen in the sediments.

Quantidade existente do nitrogênio nos sedimentos.

Quantité d'azote existant dans les sédiments.

| Area | Sediments | | | | Nitrogen in fragments of <i>Zostera</i> | |
|-------------------------|-----------|-----------------|------------------------------|-----------------|---|-----------------|
| | Total — N | | Easily decom- posable — N | | | |
| | g/m2 | Total (tons) | g/m2 | Total (tons) | g/m2 | Total (tons) |
| <i>Zostera</i> area | 71 | 2,130 | 9.3 | 280 | 5.8 | 174 |
| Non <i>Zostera</i> area | 58 | 580 | 4.3 | 43 | | |
| Whole bay | | 2,710 | | 323 | | 174 |

F. Discussion

Although the total values of several biological products may not always have high accuracy, the characteristics of productive structure of Matsushima Bay will be discussed from the above results as follows:

The productive efficiency for solar radiation energy in Matsushima Bay showed rather good agreement with that in other area. The proportion of turn over, that is, the proportion of production for the standing crop, was about 2,800 of the gross production. This value is high in comparison with that (about 77) obtained by Hogetsu and Ichimura (1954) in Suwa-lake. However, a reason for the difference may be due to the small standing crop of plankton in Matsushima Bay. These plankton samples did not contain plankton smaller than 100 μ due to the use of a plankton net with openings of about 100 μ . It is interesting that the productive efficiencies of phytoplankton, *Zostera* and laver in this bay were close to each other in the same period.

The standing crop of *Zostera* in the rapid growing stage (June) amounted to 130 tons of nitrogen. A large proportion of *Zostera* wither during July and August. Some parts flow out of the area and the fragments of dead *Zostera* are deposited on the bottom. The increase in content of soluble nutrients in the sea water occurring from July to September or to October, results from the decomposition of *Zostera*. This aids in reproduction of plankton. Furthermore, the nutrient elements in fragments of *Zostera* deposited on the bottom play an important rôle as a nutrient source for the cultured oyster through the medium of the abundant reproduction of flagellate.

A comparison between the net production of useful animals and plants and that of the others, are made as follows. Generally speaking the production of laver is much smaller than that of *Zostera*, about 3 tons-N in the laver and 130 tons-N in *Zostera*. The catch of fish and oyster correspond to only about 7% and 2% respectively in primary production or a total of about 9%. It is noted that the amount of the oyster catch was less than one third that of fish. The total of the harvested useful plant and animals amounts to 102 tons-N corresponding to 8.6% of the phytoplankton and *Zostera*.

The approximate standing crop of nitrogen in several organisms, in sea water and sediments in June (maximum growth stage of *Zostera*) was as follows:

| | | | |
|-------------------|----------|------------------------------|-------------------|
| Plankton | 0.5 tons | Sea water | less than 20 tons |
| <i>Zostera</i> | 130 " | Sediments | |
| | | easily decomposable nitrogen | 320 |
| Benthonic animals | 90 " | fragments of <i>Zostera</i> | 170 |

The standing crop of nitrogen in oyster, fish, laver and the other algae were not estimated. Hence, the amount of nitrogen in sediments (easily decomposable — N and N in *Zostera* fragments), represents a large proportion (about 60%) of the total standing crop of nitrogen in this bay, even though this total value lacks the oyster, fish and algae. It is suggested that the nitrogen in sediments plays an important rôle in the metabolic circulation of nitrogen in this bay.

Summary

The characteristics of the biological production mechanism were discussed in this chapter from the data mentioned in previous chapters. A rather high error may be introduced in the process of estimation of the amount in the whole bay from few data available. However, further investigations should give more light on this subject in the future. To gain an information on the characteristics of biological production in Matsushima Bay, a comparison was made on the following points; namely (1) the relation between the production of useful animals

and plants (commercial production) and the primary of other production, and (2) the relation between the standing crop of nitrogen in various organisms, sea water and sediments.

Consequently, annual production or catch of useful animals and plants, (fish, oyster and laver), was 8.6% of the productions of phytoplankton and *Zostera*. It is apparent that sediments play an important rôle in metabolic circulation of nitrogen in this bay.

XI — GENERAL CONCLUSIONS

The present study was designed to obtain information on the following problems: (1) characteristics of organic production and of decomposition of organic matter in Matsushima Bay, and (2) the rôle of sediments in the processes of metabolic circulation of phosphorus and nitrogen. The regional and seasonal variations of the properties of sea water in this bay were affected not only by the metabolic process of material in the water and sediments, but also by the three different water types, namely, the open water flowing through the five channels, the fresh river water flowing into the bay which is fairly rich in nutrients and the sewage water which has abundant nutrient elements.

The life-cycle of *Zostera* growing in a large area influences considerably on the chemical and physical properties of sea water and of sediments.

The textural properties of the sediments were quite different between the outer (sandy) area of the bay and the inner (muddy) area. They reflected the movement of water. The regional distributions of total-N, total-P, total-S and organic-C were observed together with the seasonal variation of their vertical distribution. Far information on dynamic movement of nutritive elements in sediments, the soluble nutrient elements in sediments and those in the interstitial water of sediments were measured. Seasonal variations of these nutrient elements showed good agreement with those in the sea water.

From the discussion on the ratios of N/P and C/N of sediments, it was concluded that these ratios rather indicate the relative content of the decomposed or undecomposed organic matter, without reference to the amount of total organic matter in sediments. Accordingly these ratios have an important significance with respect to the decomposition process of organic matter in sediments.

Observations were made on the primary production and the standing crop of net plankton. The annual average of gross production was 504 C-mg/m²/day at the central part and 1,380 C-mg/m²/day at the inner part in Shiogama Harbor, and the energy efficiency (annual average) of gross production was 0.16% at the central part and 0.45% at the inner part.

The standing crop (annual average) of net plankton expressed in terms of total-N and total-P was 6.1 mg/m³ for total-N and 0.83 mg/m³ for total-P. The most common compensation depth in this area was found to be approximately 2 to 3 meters.

Material suspended in the sea water is important from the point of view of metabolic circulation of materials.

The vertical distributions of material suspended and their seasonal variations were observed with special reference to relation between the amount of material suspended and meteorological conditions. It was evident that the seasonal variations of material suspended are influenced not only by the wind conditions such as velocity and direction of inshore wind, but also by the transportation of land soil after a heavy rainfall. The chemical properties of and organisms contained in material suspended were observed.

From the discussion on the exchange of nutrient elements between sea water and sediments, and on the metabolism of nutrients in sediments, the following points were elucidated. A considerable part of the organic matter deposited on the bottom changes to an easily decomposable form. The vertical distribution of easily decomposable nitrogen and phosphorus showed a tendency to decrease from the bottom surface to deeper layers. The rate of liberation of soluble nutrients in sediments was affected by the temperature and the bacterial activity. An experimental formula for the decomposition of organic nitrogen in the sediments was postulated. The diffusion of soluble nutrients from sediments into the overlying sea water was measured under laboratory conditions and under natural condition on the beach. The following cycle is constantly in operation in nature: precipitation of organic matter on the bottom, decomposition of organic matter, liberation of soluble nutrients, and return of these soluble nutrients into the overlying sea water.

The cyclic transformation of inorganic nitrogen in the sediments under laboratory conditions was as follows: ammonia-N → nitrite-N → nitrate-N → ammonia-N. Seasonal maxima of inorganic nitrogen in the interstitial water sediments were as follows: Ammonia-N in summer and autumn, nitrite-N in winter and nitrate-N in spring and summer. Although no large quantitatively, this nitrogen transformation is important both biochemically and ecologically.

In order to determine the quantitative variation of nitrogen at the sea bottom, theoretical discussions were made on methods measuring and analysis. In accordance with these theoretical results, an annual variation of nitrogen at bottom surface, such as the amounts of nitrogen deposited, decomposed, and consumed by the benthonic animals, was examined on the basis of the observation in Shiogama Harbor.

The life-cycle of *Zostera* growing in the bay has a great influence on the characteristic properties of sea water and sediments. The circulation of nutrients in the *Zostera* zone was examined in relation to the life-cycle of *Zostera*.

The relation between the variations of nitrogen and phosphorus in the subterranean part (stem, root-hair), in the aquatic part and the products of *Zostera* were investigated.

The seasonal variations of nitrogen in sea water, sediments and

Zostera were quite different between the *Zostera* and no *Zostera* zones especially during the rapid growing and withering stages. There is an inverse quantitative correlation in the content of nitrogen and phosphorus between *Zostera* and the sediments with relation to the life-cycle of *Zostera*. This indicates that the nitrogen and phosphorus of *Zostera* are supplied from the sediments.

Some approximated estimations of the standing crop and production of various organisms and of the existing nitrogen in sediments were calculated to show the characteristic structure of the biological production in the bay. A comparison was made between the commercial production (such as oyster, fish and laver) and the other production (plankton and *Zostera* etc.).

The sediments play an important rôle in the circulation of nutritive elements in Matsushima Bay, as indicate by the large standing crop of decomposable nitrogen in them.

The standing crop and production in the whole bay were estimated, but because of the small amount of data available, further studies should be made in order to confirm these facts.

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RESUMO

Este estudo foi efetuado com o fim de obter dados sobre a circulação metabólica do nitrogênio na água do mar, com referência a troca destes elementos com a água do mar superposta.

O estudo com esta finalidade foi efetuado na Baía de Matsushima entre 1951 e 1958. Inicialmente foram observados os efeitos da água e sedimentos da baía, tendo em vista a distribuição e a variação estacional dos caracteres físicos e químicos.

Para a estimação da produção primária e quantitativa existente, foram estudadas as características de produção na água da baía. Como, o material em suspensão na água desempenha um papel importante no processo metabólico de circulação nutritiva, a observação do mesmo prolongou-se.

Da discussão dos vários assuntos acima mencionados, que, uma atenção considerável seria dispensada a importantes elementos na circulação metabólica dos elementos nutritivos da baía.

Portanto, a experiência sobre o metabolismo dos nutrientes nos sedimentos foi realizada com referência aos problemas: a decomposição da matéria orgânica e liberação de nutrientes solúveis, pelos sedimentos, e o retorno dos mesmos pela água do mar superposta, e a transformação de nitrogênio amoniacal-N, nitrito-N e nitrato-N no interior da camada superficial.

Baseando-se nos resultados das várias condições de estudo entre os elementos nutritivos, foi discutido teoricamente para a estimação quantitativa da variação de nitrogênio na camada superficial. Além disto, foi estimada a variação também um balanço anual de nitrogênio, na camada referida.

O crescimento do ciclo de vida da *Zostera* na baía, tem influência nas propriedades características da água do mar e dos sedimentos. A circulação dos elementos nutritivos na zona da baía estudada em relação ao seu ciclo vital.

A relação entre as variações de nitrogênio e fósforo subterrânea (caule, raiz) e aquática da *Zostera* e seus produtos foi estudada.

A variação estacional de nitrogênio na água do mar, e a *Zostera*, foi completamente diferente nas zonas de *Zostera* e sem *Zostera*, especialmente durante as fases de rápido crescimento e comutação. Há uma relação quantitativa inversa no conteúdo de nitrogênio e fósforo, entre a *Zostera* e os sedimentos. Isto indica que o nitrogênio e o fósforo da *Zostera* são provenientes dos sedimentos.

Uma estimação aproximada da quantidade existente e produzida

vários organismos e existência de nitrogênio nos sedimentos, foi feita para mostrar a estrutura característica da produção biológica na baía.

Foi feita também uma comparação entre a produção comercial, ostras, peixes e Porfira, e a produção natural de plancton e *Zostera*.

Os sedimentos exercem um importante papel na circulação dos elementos nutritivos na Baía de Matsushima como indica a grande quantidade de nitrogênio decomposta.

RÉSUMÉ

Cette étude a été faite dans la baie de Matsushima de 1951 à 1958, dans le but d'élucider le problème de la circulation métabolique du phosphore et de l'azote dans les eaux de mer, et tout particulièrement les échanges entre les sédiments et les eaux du fond.

Au début de ce travail, on a étudié les caractères généraux des eaux et des sédiments de la baie en relation avec les variations régionales et saisonnières des facteurs physico-chimiques.

De même l'estimation de la production primaire a été faite et la productivité de la baie a été étudiée.

Pour vérifier les influences de la matière en suspension sur le métabolisme, la turbidité a été étudiée pendant deux ans.

Pour les discussions des nombreux faits observés, il faut noter la participation importante des sédiments dans la circulation, et le métabolisme des éléments nutritifs dans les baies peu profondes. Ainsi le métabolisme des éléments nutritifs a été étudié en relation avec la décomposition de la matière organique et la libération de produits nutritifs dans les sédiments, le retour d'éléments nutritifs des sédiments dans l'eau du fond, comme également les transformations de l'azote inorganique à la surface des sédiments.

Une méthode pour l'estimation quantitative des variations de l'azote à la surface des sédiments est discutée en se basant sur les résultats des différentes conditions du métabolisme des éléments nutritifs. De plus, on a établi les variations et le bilan annuel de l'azote à la surface des sédiments.

Le cycle vital des *Zostera* dans la baie a une grande influence sur les propriétés caractéristiques de l'eau de mer et dans les sédiments. La circulation des éléments nutritifs dans la zone des *Zostera* est examinée en rapport avec le cycle vital des *Zostera*.

On examine le rapport entre les variations de l'azote et du phosphore dans la partie souterraine (tige et poils radiculaires), la partie et les produits des *Zostera*.

La variation saisonnière de l'azote dans l'eau de mer les sédiments et les *Zostera* est entièrement différente dans les zones avec ou sans *Zostera*, spécialement durant la croissance rapide et les étapes de destruction. Il y a une relation inverse entre la teneur en azote et en phosphore dans les *Zostera* et celle dans les sédiments pendant le

cycle vital des *Zostera*. Ceci prouve que l'azote et le phosphore des *Zostera* sont fournis par les sédiments.

Une estimation approximative du stock et de la production par les différents organismes et par les sédiments a été calculée pour montrer les caractéristiques de la production biologique dans la baie.

Une comparaison fut faite entre la production commerciale (tels que huîtres, poissons et Porfira tenera) et la production naturelle (plancton et *Zostera* etc.).

Les sédiments jouent un rôle important dans la circulation des éléments nutritifs dans la baie de Matsushima, comme le montre la grande récolte d'azote décomposable existant dans les sédiments.

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