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# Sedimentation flux from mariculture of oyster (*Crassostrea gigas*) in Ofunato estuary, Japan

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Seasonal patterns of Chl *a* in water samples, sedimentation rates (total dry weight per area per day) and content of total carbon, total nitrogen, and total phosphorus in sediment trap samples, as well as in sediment samples, were measured at several stations in Ofunato estuary, Japan. High rates of sedimentation to the bottom were observed in March and September, corresponding to elevated concentrations of Chl *a*. In the middle part of the estuary, the peaks of sedimentation rate and fluxes of chemical elements through the 20-m deep layer in September amounted to 23 g $m^{-2}$ $d^{-1}$, 2200 mg C $m^{-2}$ $d^{-1}$, 290 mg N $m^{-2}$ $d^{-1}$, and 28 mg P $m^{-2}$ $d^{-1}$, coinciding with oxygen depletion in deeper layers. Seasonal changes in sedimentation can be explained by marked increases in biodeposits from oysters cultured in the surface layers. However, no marked seasonal changes in chemical elements were found within the sediment, suggesting high degradation rates of biodeposits at the sediment–water interface. Biodeposits from culture rafts were estimated using a population dynamic model for the Japanese oyster. This model gave predictions in agreement with observed seasonal changes in biodeposition fluxes through the 20-m layer in September, with a minimum estimation of 5.1 g $m^{-2}$ $d^{-1}$ with uniform seawater dispersion, and a maximum estimation of 390 g $m^{-2}$ $d^{-1}$ without dispersion.



Key words: biodeposits, Chl *a*, estuary, flux, oyster, total carbon, total nitrogen, total phosphorus.

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## Introduction

The Japanese oyster (*Crassostrea gigas*) and the Japanese common scallop (*Patinopecten yessoensis*) are two of the most important bivalves cultured commercially in the Ofunato estuary (Figure 1). Recently, production from scallop culture has dropped rapidly after harmful algal blooms were experienced (Ogata *et al.*, 1982). Since then, most bivalve harvests have come from oyster culture producing ca. 300 t wet weight of shelled meat annually (Miyazawa and Hayakawa, 1994). Oysters are cultured for two years by the hanging method from rafts (Figure 2). During their second year, they are kept in the upper 6 m of the water column, where Chl *a* is more abundant, until they reach commercial size. During their first year they are held in deeper layers to be moved up the next year. The average density of oysters under rafts amounts to 1100 individuals $m^{-2}$ (ca. 50 000 per raft) and about 2500 rafts were arranged in the estuary, covering 1.3% of the estuarine surface area of ca. 7.7 $km^2$. Scallop rafts have 12–17 clusters of 15–20 shells per rope.

Depletion of dissolved oxygen (DO) has occurred near the bottom at station OF06 (depth 26 m; Figure 1) in summer, but only a slight decrease in DO was observed at OF15 outside the sill (Hayakawa, 1990). DO depletion near the bottom was attributed to high concentrations of Chl *a* in the estuary, heavy biodeposition of organic matter, reduced advection and diffusion due to summer stratification, and little exchange of seawater in

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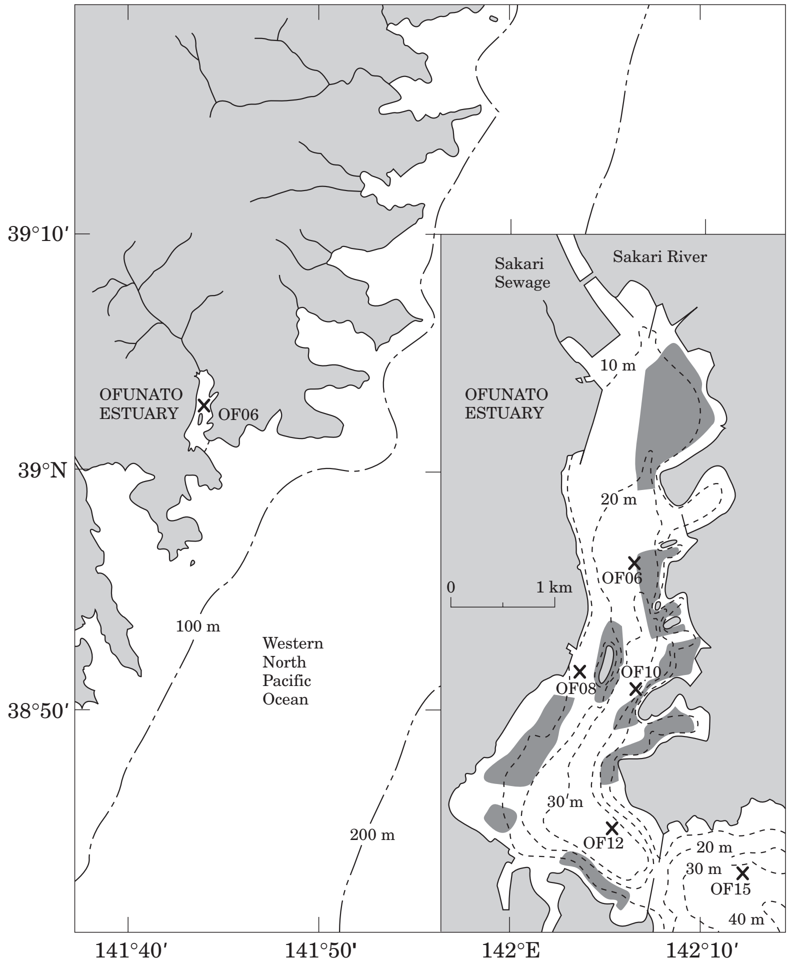


Figure 1. Sampling locations in Ofunato estuary (sedimentation flux was measured at OF06, OF08, OF10, and OF12, water quality at OF06 and OF15, and sediment at OF06 and OF12; shaded: areas with rafts for oyster culture).

deeper layers. The considerable depth of the estuary may protect mariculture at the surface from serious damage by anoxic waters at the bottom.

Haven and Morales-Alamo (1966) and Kusuki (1977a,b) have carried out pioneer work measuring biodeposition by the American oyster (*Crassostrea virginica*) and *C. gigas*, respectively. Powell *et al.* (1992) and Hofmann *et al.* (1992, 1994) have recently developed models for populations of *C. virginica*. Kobayashi *et al.* (1997) have applied these to Japanese oyster populations and presented a population dynamics model that includes integrated mathematical descriptions of feeding, assimilation, growth, and reproduction, which are forced by ambient physical and chemical factors.

We summarize averaged seasonal patterns of (1) Chl *a* as a measure of the main particulate organic food, (2) sedimentation consisting mainly of biodeposits from oyster rafts, and (3) sediment quality near the rafts. We also compare (4) measured sedimentation rates with model-based estimates.

## Materials and methods

The Ofunato estuary is located on the northeastern coast of Japan. It has a maximum depth of 38 m and a sill depth of 15 m at the mouth (Figure 1). Tidal ranges of 1.0–1.5 m and tidal current velocities of 10–15 and <5 cm $s^{-1}$ in surface and bottom waters, respectively, have been observed near Stn OF06. Bottom substrates deeper than 10 m consist mainly of silt/clay.

Sedimentation samples were collected monthly with sediment traps at 5, 10, 15, and 20 m moored at OF06 (Jan 1985–Dec 1994), OF08 (Feb 1995–Sep 1996), OF10 (Feb 1995–Sep 1996), and OF12 (Jan 1988–Dec 1989 and Jan 1992–Dec 1994). Most stations were located

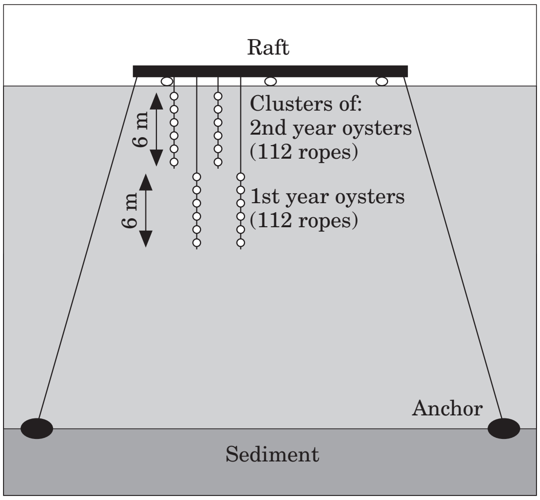


Figure 2. Typical oyster raft (4.5 × 10 m; average density: 11 000 $m^{-2}$) set-up in the Ofunato estuary: lower clusters consist of small oysters during their 1st year, upper clusters of oysters during their 2nd year (see also text).

near or between oyster rafts. Sediment traps consisted of three polyethylene cylinders (11 cm diameter and 25 cm high), and were set at each depth for 3 d. The samples were filtered onto glass fibre filters (Whatman, GF/C), washed with distilled water to remove salts and dried at 110°C for 2 h to measure their dry weight for calculation of sedimentation rates. Total carbon (TC), total organic carbon (TOC), and total nitrogen (TN) were measured with a CN analyzer (Yanaco, MT-500). TOC was measured after overnight treatment with 1 N hydrochloric acid to remove inorganic carbonates. Total phosphorus (TP) was measured by the method of Strickland and Parsons (1968), after chemical digestion with perchloric acid on a hot plate. Fluxes of TC, TOC, TN, and TP were estimated as the products of sedimentation rates and their chemical contents.

Sediment sampling was carried out monthly with a core sampler (2.5 cm diameter) at OF06 (Jan 1985–Dec 1992) and OF12 (Jan 1984–Dec 1985, and Jan 1988–Dec 1992). These samples were divided into five slices of 0–2, 2–4, 4–6, 6–8, and 8–10 cm depth layers. Dried samples

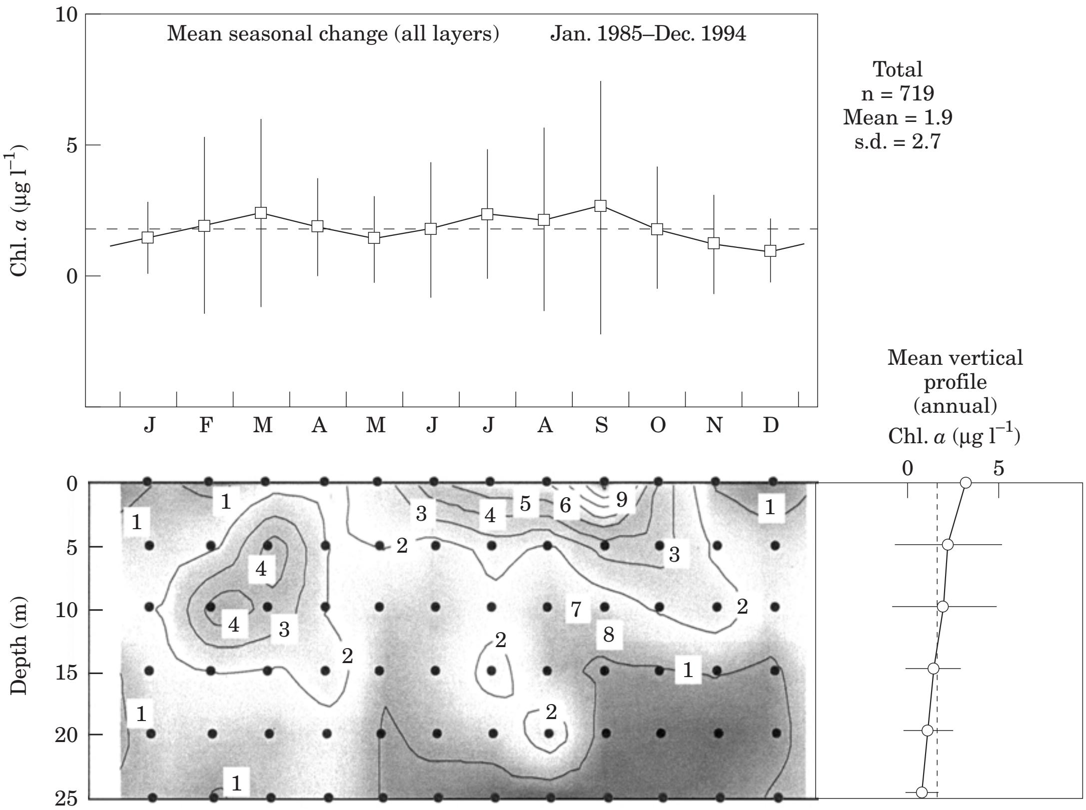


Figure 3. Monthly changes in mean Chl *a* at station OF06, 1985–1994: isopleths, average over all layers (top) and annual mean vertical profile (right), with standard deviations (broken lines indicate the overall mean value).

Table 1. Mean concentrations and standard deviations (mg $g^{-1}$) of total carbon (TC), total organic carbon (TOC), total nitrogen (TN), and total phosphorus (TP) in sediment trap samples taken at stations OF06, OF08, OF10, and OF12 (see Figure 1) over the period 1985–1996.

| Layer | TC | TOC | TN | TP |
|---|---|---|---|---|
| 5 m | | | | |
| Mean | 106 | — | 12 | 1.8 |
| s.d. | 40 | — | 9 | 1.2 |
| n | 159 | — | 159 | 129 |
| 10 m | | | | |
| Mean | 104 | 76 | 11 | 1.6 |
| s.d. | 43 | 16 | 6 | 1.1 |
| n | 217 | 9 | 217 | 188 |
| 15 m | | | | |
| Mean | 97 | — | 11 | 1.6 |
| s.d. | 27 | — | 4 | 1.1 |
| n | 159 | — | 159 | 129 |
| 20 m | | | | |
| Mean | 93 | 70 | 11 | 1.4 |
| s.d. | 30 | 20 | 5 | 0.9 |
| n | 193 | 27 | 192 | 175 |
| 30 m | | | | |
| Mean | 85 | — | 9 | 1.4 |
| s.d. | 33 | — | 5 | 0.8 |
| n | 77 | — | 77 | 60 |
| 33 m | | | | |
| Mean | 110 | 73 | 14 | — |
| s.d. | 20 | 25 | 11 | — |
| n | 20 | 27 | 17 | — |
| All | | | | |
| Mean | 99 | 72 | 11 | 1.6 |
| s.d. | 36 | 21 | 6 | 1.0 |
| n | 825 | 63 | 821 | 681 |

Table 2. Means and standard deviations (mg $m^{-2}$ $d^{-1}$) of sedimentation rates and fluxes of total carbon (TC), total nitrogen (TN), and total phosphorus (TP) in sediment trap samples (cf. also Table 1).

| Layer | Sedimentation | TC | TN | TP |
|---|---|---|---|---|
| 5 m | | | | |
| Mean | 5 600 | 530 | 58 | 10 |
| s.d. | 5 000 | 370 | 48 | 7 |
| n | 160 | 159 | 159 | 129 |
| 10 m | | | | |
| Mean | 7 400 | 700 | 80 | 11 |
| s.d. | 6 300 | 570 | 74 | 9 |
| n | 219 | 217 | 217 | 188 |
| 15 m | | | | |
| Mean | 12 000 | 1 100 | 130 | 18 |
| s.d. | 7 000 | 620 | 81 | 13 |
| n | 160 | 159 | 159 | 129 |
| 20 m | | | | |
| Mean | 11 000 | 1 000 | 120 | 14 |
| s.d. | 8 200 | 710 | 92 | 13 |
| n | 195 | 193 | 192 | 175 |
| 30 m | | | | |
| Mean | 6 300 | 480 | 51 | 7 |
| s.d. | 6 000 | 420 | 44 | 7 |
| n | 77 | 77 | 77 | 60 |
| 33 m | | | | |
| Mean | 6 500 | 710 | 100 | — |
| s.d. | 2 900 | 370 | 97 | — |
| n | 20 | 20 | 17 | — |
| All | | | | |
| Mean | 8 200 | 800 | 88 | 13 |
| s.d. | 6 900 | 610 | 78 | 11 |
| n | 831 | 825 | 821 | 681 |

were analyzed for TC, TN, and TP by the methods described above.

Biodeposition was calculated by the population dynamics model of Kobayashi *et al*. (1997), which depends on water temperature, salinity, Chl *a*, and suspended solids (SS). These parameters were monitored monthly. After filtration of water samples through glass fibre filters, Chl *a* was measured at OF06 (Jan 1985–Dec 1994) after Jeffrey and Humphrey (1975). SS was measured at OF10 (May 1995–Jun 1996). Averaged seasonal changes in water temperature and salinity at OF06 came from the data (Apr 1979–Mar 1989) of Hayakawa (1990). Data sets of averaged seasonal changes in environmental factors in the estuary were prepared to provide environmental inputs for the oyster model.

In the biodeposition model, oysters were classified in ten size classes, ranging from 0.3–2.5 mm up to 115–130 mm length, with biological parameters specific for each size class. The filtration rate depended on water temperature, salinity, and SS. Filtration rate times the ambient food concentration (a function of Chl *a*) predicts the potential total ingestion. Assimilation efficiency was assumed to be constant at 0.75. Thus, non-assimilated food, or biodeposition including both faeces and pseudofaeces, was estimated as 25% of total ingestion. Reproductive efficiency depended on water temperature. When gonadal weight is 50% of the total weight, the oyster starts spawning, which is accompanied by considerable loss of body weight. Model predictions were continued for two years from May 1 (120th Julian day) with a time step of 1 d. Ambient parameters in the 0–10 m layer at OF06 were assumed to vary seasonally according to the averaged values, with ranges of water temperature of 6.6–23.1°C, salinity of 20.49–33.84 psu, Chl *a* of 0.8–9.2 µg $l^{-1}$ and SS of 0.3–4.4 mg $l^{-1}$.

The model was run under two assumptions: (1) without dispersion it provides the maximum local rates of deposition; (2) with uniform dispersion throughout the whole estuary a minimum estimate of the flux to the bottom under the rafts is obtained. Uniform dispersion

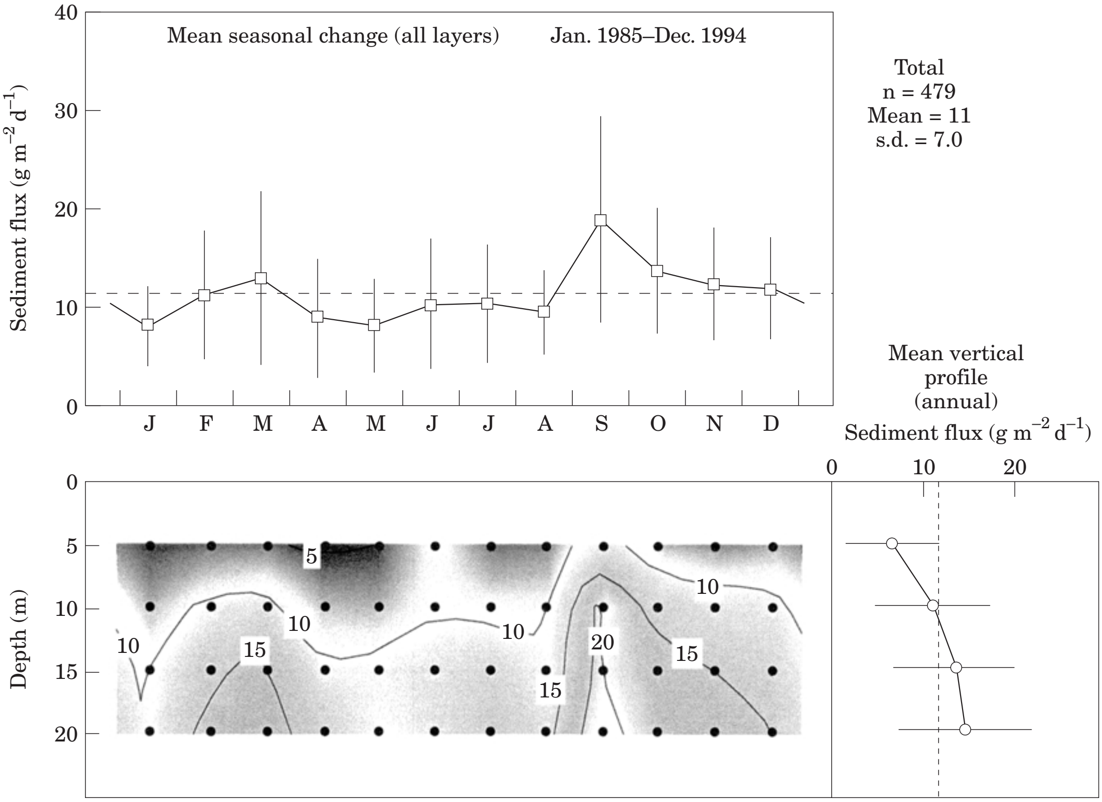


Figure 4. Monthly changes in mean sedimentation rate at station OF06, 1985–1994 (see Figure 3 for details).

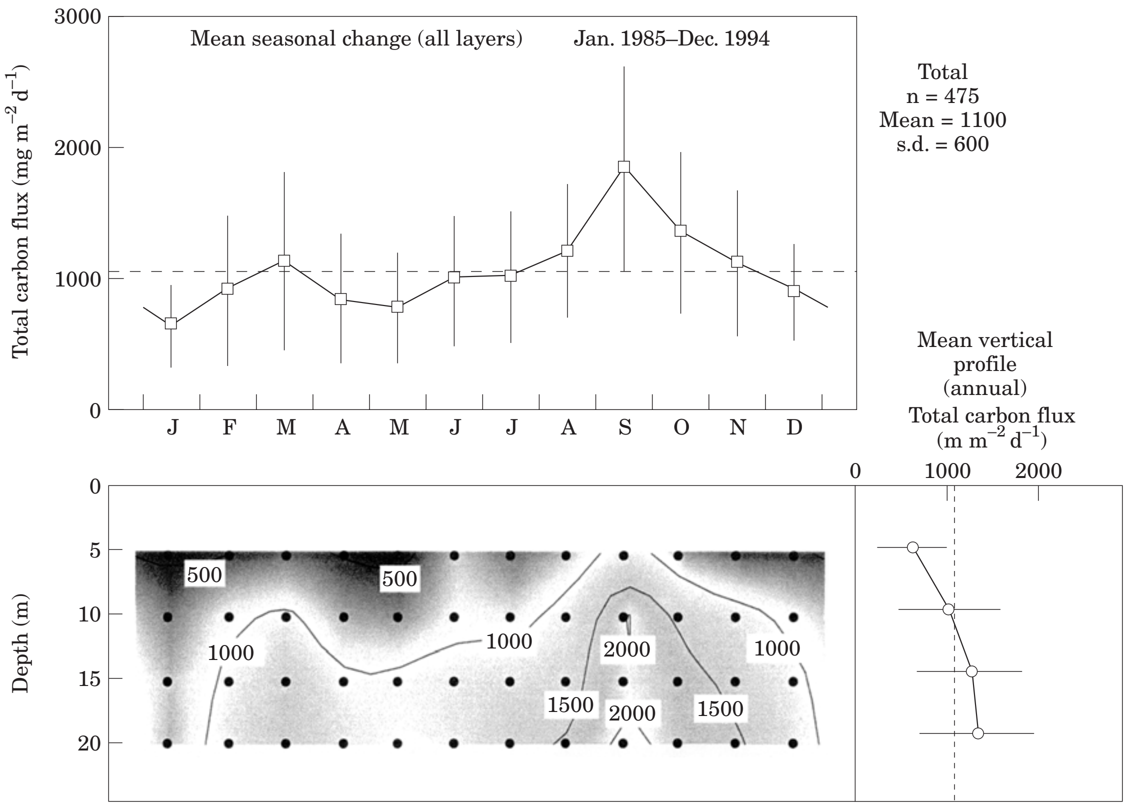


Figure 5. Monthly changes in mean total carbon flux at station OF06, 1985–1994 (see Figure 3 for details).

Table 3. Contents (arithmetic mean concentration in mg $g^{-1}$ and standard deviations) of total carbon (TC), total nitrogen (TN), and total phosphorus (TP) in sediment samples from two stations in Ofunato estuary (OF06: depth 26 m, period 1985–1992; OF12: 38 m, 1984–1992; n: number of data points).

| | TC | | TN | | TP | |
|---|---|---|---|---|---|---|
| Layer | OF06 | OF12 | OF06 | OF12 | OF06 | OF12 |
| 0–2 cm | | | | | | |
| Mean | 45 | 46 | 3.4 | 3.8 | 0.72 | 0.65 |
| s.d. | 8 | 8 | 0.7 | 1.4 | 0.32 | 0.24 |
| n | 89 | 71 | 89 | 71 | 89 | 72 |
| 2–4 cm | | | | | | |
| Mean | 44 | 43 | 2.8 | 2.2 | 0.64 | 0.52 |
| s.d. | 7 | 8 | 0.6 | 0.8 | 0.28 | 0.20 |
| n | 69 | 24 | 69 | 24 | 69 | 24 |
| 4–6 cm | | | | | | |
| Mean | 41 | 44 | 2.6 | 1.8 | 0.58 | 0.50 |
| s.d. | 6 | 6 | 0.7 | 0.7 | 0.27 | 0.19 |
| n | 68 | 23 | 68 | 23 | 68 | 23 |
| 6–8 cm | | | | | | |
| Mean | 40 | 44 | 2.5 | 1.5 | 0.56 | 0.45 |
| s.d. | 6 | 6 | 0.7 | 0.6 | 0.33 | 0.24 |
| n | 68 | 23 | 68 | 23 | 68 | 23 |
| 8–10 cm | | | | | | |
| Mean | 39 | 43 | 2.4 | 1.5 | 0.56 | 0.45 |
| s.d. | 5 | 4 | 0.7 | 0.6 | 0.68 | 0.21 |
| n | 48 | 23 | 48 | 23 | 48 | 23 |
| All | | | | | | |
| Mean | 42 | 45 | 2.8 | 2.7 | 0.62 | 0.56 |
| s.d. | 7 | 7 | 0.8 | 1.5 | 0.30 | 0.24 |
| n | 342 | 164 | 342 | 164 | 342 | 165 |

is mimicked by applying the ratio of the area occupied by rafts to the area of the estuary (0.013) in the calculations.

## Results and discussion

Mean seasonal changes in Chl *a* at OF06 (Figure 3) indicated high values in the 0–10 m layer from February to April and in the 0–5 m layer from May to October. Low values were observed near the bottom in late summer (isopleths were drawn on the basis of the monthly means). The mean seasonal change over all layers, and the average annual vertical profile are also shown (based on individual data, not on monthly means).

The maximum average Chl *a* content of the 0–10 m water column at OF06 was 46 mg $m^{-2}$ in September. This value corresponds roughly to 1400–4600 mg C $m^{-2}$, 230–770 mg N $m^{-2}$ and 35–120 mg P $m^{-2}$ according to the ratios of organic carbon to Chl *a* (30–100), to nitrogen (6) and to phosphorus (40) of phytoplankton (Parsons *et al.*, 1984). It follows that just the top 10-m water column in September could produce 870–8400 mg C $m^{-2}$ $d^{-1}$, 140–1400 mg N $m^{-2}$ $d^{-1}$, and 22–210 mg P $m^{-2}$ $d^{-1}$, if specific growth rates of phytoplankton in nutrient-rich waters ranged from 0.7 to 1.5 doublings $d^{-1}$ (Parsons *et al.*, 1984). These values would present the maximum food supply for oysters in the estuary. They are higher than those estimated (788 mgC $m^{-2}$ $d^{-1}$, 139 mgN $m^{-2}$ $d^{-1}$, and 19.2 mgP $m^{-2}$ $d^{-1}$) at an offshore station in Funka Bay (depth 94 m) in July by using the $^{14}$C method (Yanada and Maita, 1978).

The average contents of TC, TOC, TN, and TP in sediment trap samples are presented in Table 1. Mean values for individual stations (measured in different years) ranged between 93 and 110 mg $g^{-1}$ for TC, 65 and 76 mg $g^{-1}$ for TOC, 9.3 and 14 mg $g^{-1}$ for TN, and 1.4 and 3.1 mg $g^{-1}$ for TP. TOC amounted to ca. 70% of TC. There was little difference between layers. However, a seasonal trend was present with values lowest in winter and highest in summer: monthly means of TC at OF06 reached a minimum of 77 mg $g^{-1}$ in December and a maximum of 130 mg $g^{-1}$ in August; TN ranged from 7.3 mg $g^{-1}$ in January to 15 mg $g^{-1}$ in August; and TP from 1.2 mg $g^{-1}$ in November to 2.0 mg $g^{-1}$ in August.

Haven and Morales-Alamo (1966) reported mean values of TOC of 46–61 mg $g^{-1}$ for faeces and 54–59 mg $g^{-1}$ for pseudofaeces of *C. virginica*, while Kusuki (1977b) reported TOC values of 30–120 mg $g^{-1}$ and TN values of 4–15 mg $g^{-1}$ for *C. gigas*. These values are comparable with the TOC content of our sediment trap samples (65–76 mg $g^{-1}$), suggesting that the latter consisted mainly of biodeposits from oysters.

Sedimentation rates (total dry weight per area per day) are given in Table 2. Total means ranged from 2.9 to 11 g $m^{-2}$ $d^{-1}$ among stations. Mean seasonal changes at OF06 showed peaks in March and in September (Figure 4). The mean sedimentation rate through the 20-m layer to the bottom reached a maximum of 23 g $m^{-2}$ $d^{-1}$ in September.

Seasonal changes in particle fluxes corresponded to those in Chl *a*. Haven and Morales-Alamo (1966) estimated the mean total dry weight of biodeposits (faeces plus pseudofaeces) per individual for *C. virginica* as 0.23 g $d^{-1}$, with a maximum of 0.56 g $d^{-1}$, while Kusuki (1977a) reported a maximum value of 0.24 g $d^{-1}$ for individual *C. gigas*. Therefore, the maximum rate of 23 g $m^{-2}$ $d^{-1}$ in September at OF06 nearest to the rafts could be caused by biodeposits from ca. 100 oysters $m^{-2}$. Because the oyster density on the rafts was 1100 individuals $m^{-2}$, more than 260 g $m^{-2}$ $d^{-1}$ might be deposited directly beneath the raft without any dispersion. The difference between this value and the average sedimentation rates observed (2.9–11 g $m^{-2}$ $d^{-1}$) suggests that dispersion by water currents is an important factor. We conclude that seasonal changes in sedimentation were characterized by marked increases in late summer biodeposits from oysters.

Fluxes of TC (Figure 5), TN, and TP varied seasonally, corresponding to sedimentation rates (Table 2).

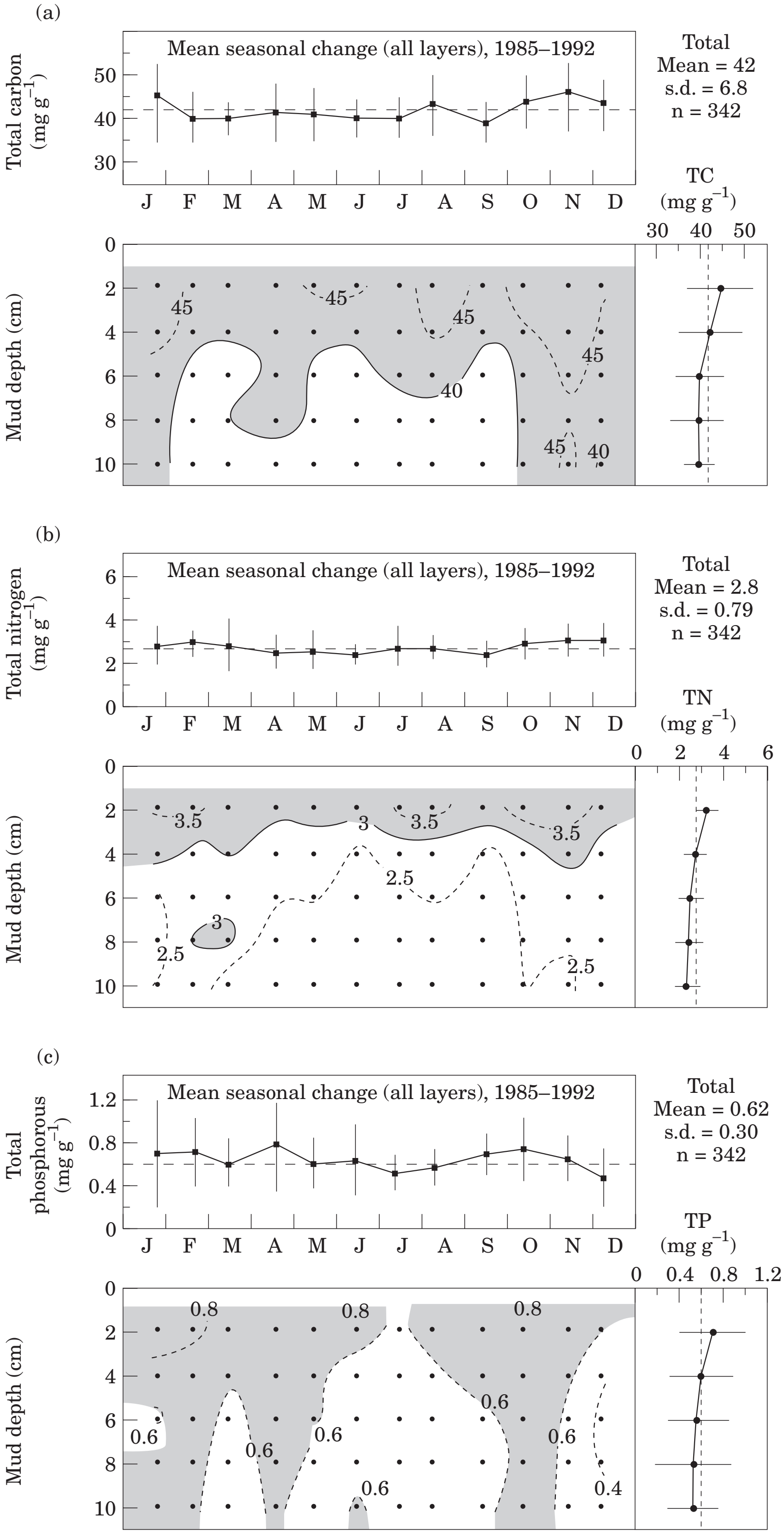


Figure 6. Monthly changes in mean content of (a) total carbon, (b) total nitrogen, and (c) total phosphorus in sediment samples at station OF06, 1985–1992 (see Figure 3 for details).

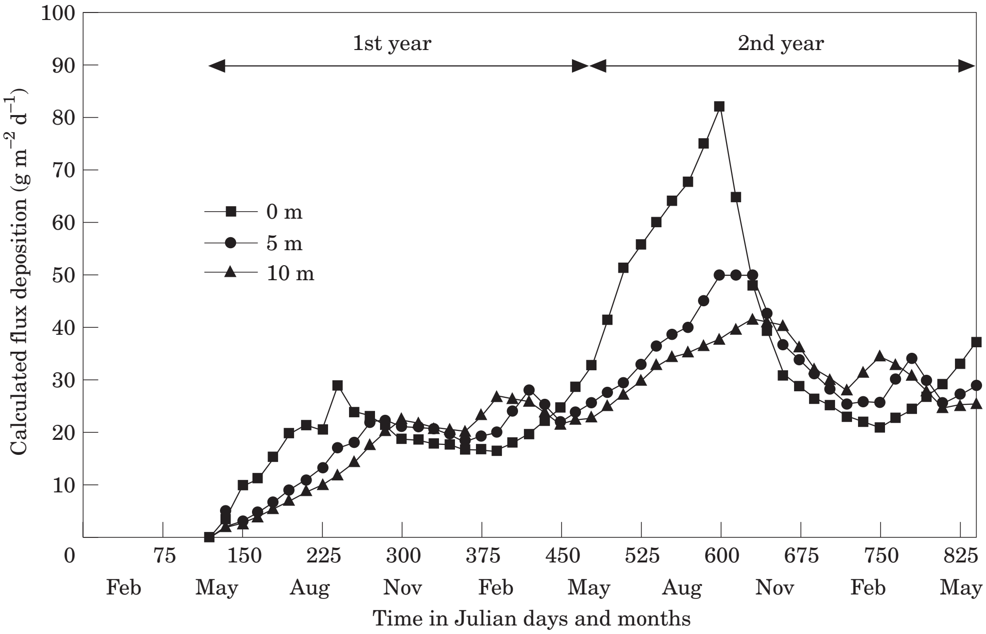


Figure 7. Temporal change in the calculated fluxes of biodeposition at three depths from a batch of cultured oysters (density: 100 m$^{-2}$) during their development according to the model. —■—, 0 m; —●—, 5 m; —▲—, 10 m.

Fluxes through the deeper layers were higher than through the surficial layers, suggesting that biodeposit production surpassed their degradation in deeper layers. The maximum of TC fluxes through the 20-m layer was 2200 mg C m$^{-2}$ d$^{-1}$ in September, which coincided with DO depletion (Hayakawa, 1990). TOC fluxes (not shown) were ca. 70% of TC fluxes in the same layers. Thus, the maximum TOC flux estimated for OF06 was 1500 mg C m$^{-2}$ d$^{-1}$. DO could be removed at the daily rate of ca. 1 ppm from the 5-m water column above the bottom if complete oxidative decomposition occurred (106 moles of carbon react with 138 moles of molecular oxygen $O_2$). The maximum fluxes of TN and TP through the 20 m layer at OF06 in September were 290 mg N m$^{-2}$ d$^{-1}$ and 28 mg P m$^{-2}$ d$^{-1}$, and means were 120 mg N m$^{-2}$ d$^{-1}$ and 16 mg P m$^{-2}$ d$^{-1}$, respectively.

The maximum fluxes were within, or comparable to, the estimated fluxes from primary production produced by the top 10 m of the water column in September (870–8400 mg C m$^{-2}$ d$^{-1}$, 140–1400 mg N m$^{-2}$ d$^{-1}$, and 22–210 mg P m$^{-2}$ d$^{-1}$). Deposition fluxes of TN and TP might be balanced by the inorganic fluxes of 56 mg N m$^{-2}$ d$^{-1}$ and 3 mg P m$^{-2}$ d$^{-1}$ estimated after Hayakawa (1986) and the organic fluxes from sewage, as well as a considerable supply from offshore waters during winter.

Contents of TC, TN, and TP in sediment samples are given in Table 3. Values were highest in the surface layer of 0–2 cm at OF06, but less than those of sediment trap samples because of the higher amount of inorganic substrate such as silt and clay. Mean seasonal changes showed no apparent trend (Figure 6).

Iwasaki *et al.* (1987) reported the highest contents of sediments as 31 mg C g$^{-1}$ for TC and 3.6 mg N g$^{-1}$ for TN in Ise Bay, which are values comparable to the means for the Ofunato estuary. Although highest sedimentation rates were observed in September, there were no seasonal trends in elemental composition within sediments. This suggests that biodeposits are degraded rapidly at the sediment–water interface. Lancelot and Billen (1985) reported nitrogen release rates of 13–140 mg N m$^{-2}$ d$^{-1}$ from the oxidized sediment surface and denitrification rates of 2–190 mg N m$^{-2}$ d$^{-1}$ from the anoxic layers. Thus, the highest reported degradation rates of nitrogen are still well below the maximum fluxes of TN (290 mg m$^{-2}$ d$^{-1}$) observed, but they would suffice to balance the average annual fluxes.

Calculated biodeposition by 100 oysters in the 0-m layer showed remarkable peaks in September (Figure 7). Biodeposition remained low from fall to spring, with a rapid decrease after spawning followed by reduced filtration rates owing to autumn cooling. High Chl *a* concentrations in the 5–10 m layer (Figure 3) caused the spring increase in biodeposits. Modelled individual oysters produced wastes depending on their size class. Mean deposits ranged from ca. 0.2–0.8 g d$^{-1}$ per individual and exceeded the value of 0.24 g d$^{-1}$ reported by Kusuki (1977a).

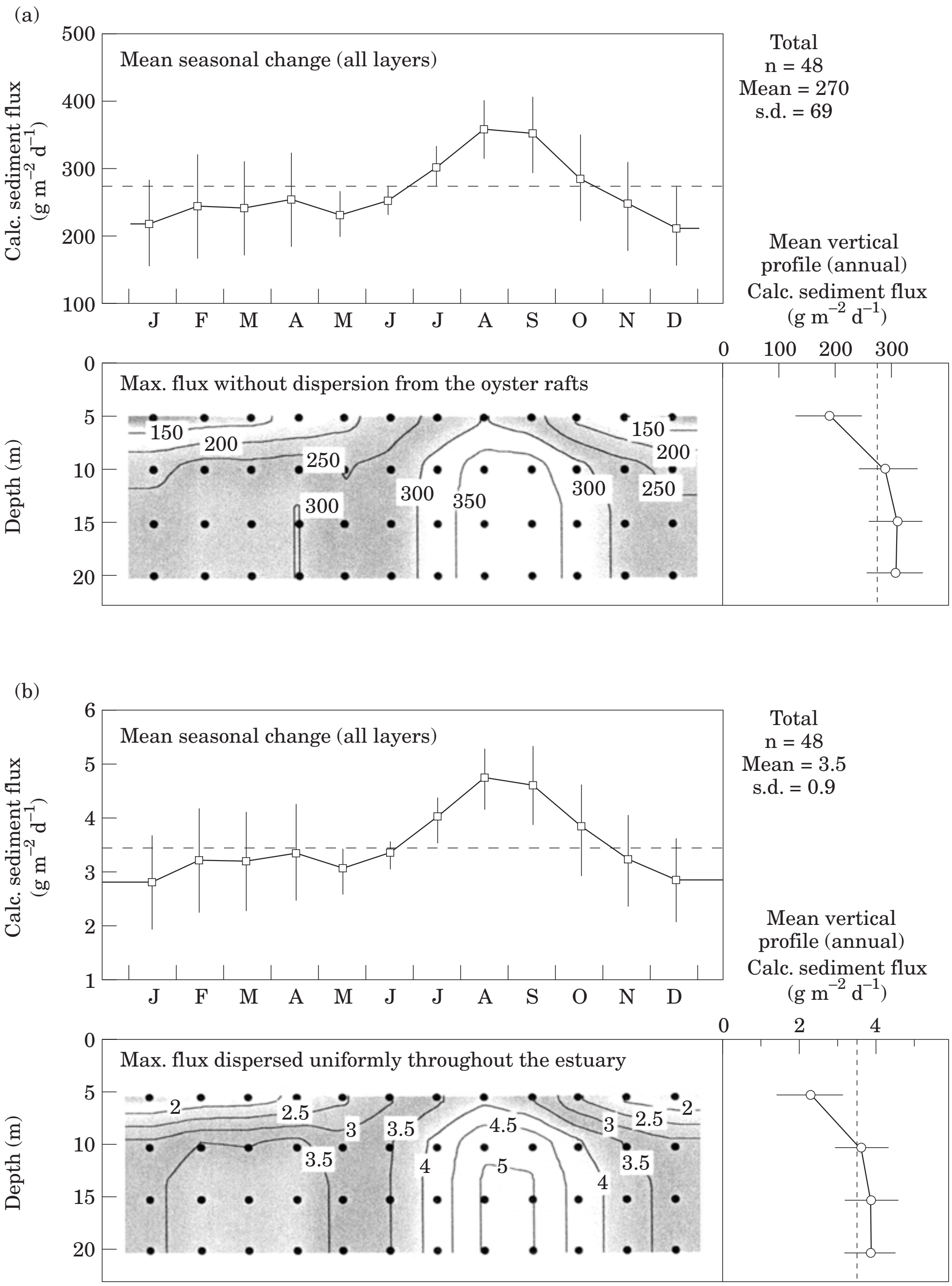


Figure 8. Calculated seasonal changes in the maximum [(a); no dispersion] and the minimum [(b); uniform dispersion throughout the estuary] bidodeposition flux according to the model (see Figure 3 for details).

Sedimentation of biodeposits, without degradation in the 5–20 m layers, was estimated by taking the population density for each age group into consideration. Figure 8 shows the seasonal changes in maximum (without dispersion) and minimum (by multiplying the ratio of raft area to total estuarine area by 0.013) biodeposition. These calculations gave a minimum estimate of 5.1 g $m^{-2}$ $d^{-1}$ and a maximum of 390 g $m^{-2}$ $d^{-1}$ for the 20 m layer in September. Annual means were 3.5 g $m^{-2}$ $d^{-1}$ and 270 g $m^{-2}$ $d^{-1}$, respectively. The seasonal changes were comparable with those observed (Figure 4) but the observed mean sedimentation rates (2.9–11 g $m^{-2}$ $d^{-1}$) were closer to the minimum estimate, suggesting a considerable rate of dispersion.

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