Abstract.—Annual fluctuation in the number of newly settled juveniles and in the stock size of the sunray surf clam, *Mactra chinensis*, were examined from 1987 to 1994 off the coast of Tomakomai, southwest Hokkaido. Stock size was estimated with a model based on two known population parameters, juvenile density and age composition. Juvenile density and the stock size (or mass) ranges were 1.3 to 157.0 ind./m^2 and 249.8 to 1,127.4 metric tons, respectively; a time lag between the relative fluctuations of both agreed with age-at-recruitment to the stock. Our results suggest that population dynamics are directly influenced by the number of juveniles. The predicted stock size approximated the measured value and, consequently, a long-term prediction of stock size was deemed possible, provided age composition and juvenile density are determined.

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Population dynamics and stock size prediction for the sunray surfclam, *Mactra chinensis*, at Tomakomai, southwest Hokkaido, Japan

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The sunray surfclam, *Mactra chinensis*, is a commercially important bivalve belonging to the family Mactridae and is widely distributed on the upper subtidal sandy bottom off the coast of Japan, China, Korea, Sakhalin, and the maritime province of Siberia (Habe, 1977). This clam has been harvested from marine waters off Hokkaido as incidental catch in the fishery for Japanese surfclam, *Pseudocardium sachalinensis*, which is the most commercially important bivalve in northern Japan (Kinoshita and Terai, 1954).

Recently, the demand for *M. chinensis* caught off Hokkaido has increased owing to decreasing catches on Honshu Island (Kurata, 1991). However, from 1985 to 1994, the annual Hokkaido catch fluctuated between 705 and 1,310 metric tons. In response to this wide fluctuation, stock management plans are now required. Although there are some studies of the breeding season (Miyazaki, 1957; Tomita, 1974), growth (Hanaoka and Shimazu, 1949), spatial distribution (Hayashi et al., 1965, 1967), increase in the number of juveniles (Inoue and Ozu, 1960; Yoshimatsu, 1977), and catch fluctuation (Saito et al., 1982), these studies have provided only fragmentary information. Of necessity, several temporary stock management measures, similar to those used for *P. sachalinensis*, have been implemented by several fisheries cooperative associations in Hokkaido to regulate the fishery for *M. chinensis* . These measures include limiting allowable catch and imposing a minimum harvestable shell length and period or area for fishing. We have systematically studied the life history of *M. chinensis* and have already reported on its reproductive cycle (Sakurai et al., 1992), age at first maturation (Sakurai et al., 1992), relation between age and growth (Sakurai, 1993), spatial distribution pattern (Sakurai, 1994), and annual mortality rate (Sakurai, 1996) off the coast of Tomakomai, southwest Hokkaido, Japan.

The aim of this study is first to examine the fluctuation in density of newly settled and harvestable-size *M. chinensis* at Tomakomai and to predict the stock size according to the population parameters that we have already reported.

Materials and methods

Study area

The study was conducted on a subtidal sandy bottom off Tomakomai (42°36'N, 141°32'E), where *M. chinensis* with shells longer than 60 mm are harvested commercially. Figure 1 shows the survey area in relation to the entire fishing ground, which is about 32 km^2 in area. The survey area is situated on the fishing grounds within 6 km of shore and covers depth ranges from 3 to 11 m. The sediment in the area is fine or very fine sand with low organic carbon content, less than 0.3% of dry weight (Sakurai et al., 1991). The bottom water temperature at 10-m depth ranges between 3.0°C in March and 20.2°C in September (Sakurai, 1993).

Sampling and processing of clams

The breeding season of *M. chinensis* occurs between July and September at Tomakomai (Sakurai et al., 1992), the planktonic larval period lasts for 14–21 days (Tsurui, 1980; Kobayashi and Ujima, 1983), and shells of newly settled juveniles grow to 1–3 mm long between September and November (Sakurai, 1994). The density of newly settled juveniles was therefore

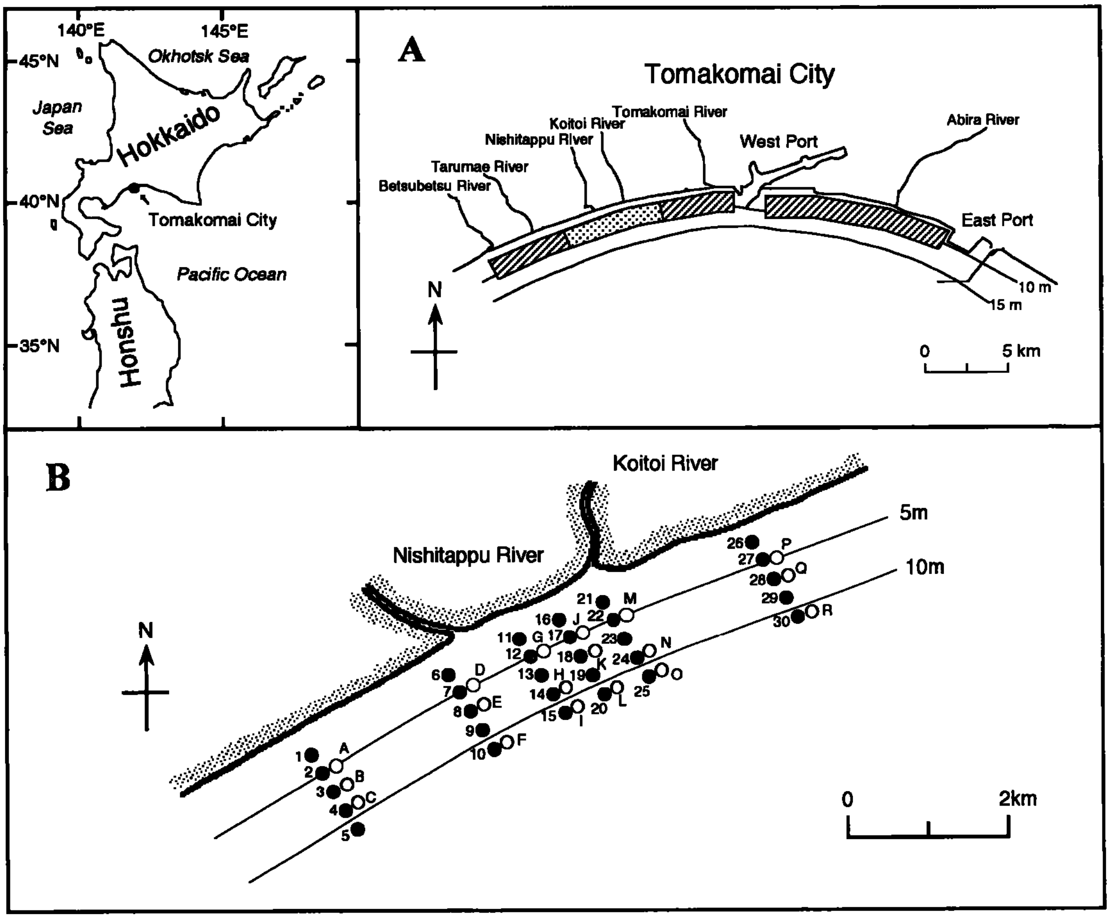

Figure 1

Location of the survey area off the coast of Tomakomai, southwest Hokkaido, Japan. (**A**) Shaded and dotted portions represent the entire fishing ground of *M. Chinensis*; dotted portion represents the survey area. (**B**) Solid and open circles indicate stations sampled by a Smith-McIntyre grab sampler and Japanese surfclam hydraulic jet dredge, respectively.

investigated during September and November in 1987–94 as tabulated in Table 1. Thirty sampling stations used for the collection of juveniles were arranged as shown in Figure 1. Each of the stations was set up at six transects including depths of 3, 5, 7, 9, and 11 m for evaluating the average density of juveniles in the fishing ground. The distribution of juveniles had been previously observed at 9 m, parallel to the shoreline in Tomakomai (Sakurai, 1994). Two samples were collected at each station with a Smith-McIntyre grab (sampling area: 0.05 m^2), sieved through a 1-mm mesh, and preserved immediately in 5% buffered formalin in the field. Sorting, identification based on morphological characteristic of the shell (Habe, 1977), and counting of juveniles were done in the laboratory.

Harvestable-size clams with shells >60 mm long were collected at 18 sampling stations in April, 1987–94 (Fig. 1; Table 1). Samples were collected with a hydraulic jet dredge (width=1.2 m, mesh size of net bag=70 mm, spacing of teeth=36 mm, and angle of tooth=60°) normally used for collecting *P. sachalinensis*. The dredge was towed parallel to shore for 50–100 m at each station. Distance of each tow was estimated by measuring the length of the dredge-connected rope wrapped by a winch. Sorting was conducted in the field. Shell lengths were measured to the nearest 0.1 mm with a sliding caliper in the laboratory. Clams with shells >60 mm long were grouped into 5-mm intervals and counted at each station. These counts were subsequently adjusted on the basis of catch efficiencies of the dredge for the different 5-mm-long intervals (60–65 mm to 0.75, 65–70 mm to 0.82, 70–75 mm to 0.88, 75–80 mm to 0.95, and >80 mm to 1.00), which were based on the selectivity curve of *M. chinensis* (Nashimoto, 1984), before density (ind./sample area) was estimated. The density was then converted to biomass (g/sample area) by using the weight (g) equivalent for the median shell length of each size interval. The length-weight equivalent was determined from 107 clams with shells 57.8–83.4 mm long sampled at station N (Fig. 1) in April 1991 as follows:

$$\log W = 3.16 \log L - 4.071, \quad (r = 0.9728, P < 0.01) \quad (1)$$

where W = the weight (g); and
L = the shell length (mm).

Next, the stock size (N_e; unit: t [age in years]) in the survey area was estimated with the following equation:

$$N_e = 18^{-1} A \sum_{i=1}^{18} b_i l_i^{-1} w^{-1} \times 10^{-6} \quad (2)$$

where A = survey area (72×105 m^2);
b_i = biomass (g/sample area) at each station;
l_i = tow distance (m) at each station; and
w = width of the dredge (1.2 m).

In *M. chinensis*, an external growth ring with a light penetrable band, as shown in Figure 2, is formed annually on the shell during declining water temperature, November–January, and is able to be distinguished from other rings (Sakurai, 1993). For the stock size prediction, therefore, the age of clams was determined by counting these rings. Clams with shells >60 mm long sampled at station N (Fig. 1) in April 1991 were used for age determination because the distribution of harvestable-size *M. chinensis* was observed at 9 m parallel to the shoreline in Tomakomai (Sakurai, 1996) and because specimens were considered typical of age composition in the survey area. Age determination was conducted by first washing out the shell periostracum of the specimens with a chlorine bleaching agent and by drying it in the shade. Next, the specimens were put on a light box, and external growth rings with light penetrable bands were counted.

Age-determined clams were grouped into 5-mm intervals at each age and counted. These counts (ind./sample area) were adjusted by using the above efficiencies, and then density (ind./m^2) was estimated at each age by multiplying the counts by tow distance and width of the dredge.

Table 1

Sampling dates of newly settled juveniles and harvestable-size clams of *M. chinensis*.

Year	Newly settled juveniles	Harvest-size clams
1987	20 Nov	2–5 Apr
1988	15 Nov	1–4 Apr
1989	21 Nov	2–5 Apr
1990	4 Sep	11, 12 Apr
1991	26 Nov	10, 11 Apr
1992	15 Oct	16, 18 Apr
1993	20 Sep	12, 13 Apr
1994	29 Nov	20, 21 Apr

Stock size prediction

The predicted stock size (N_{pi}; i=1992,1993, . . . , 1997; unit: t), based on the age composition in April 1991, was estimated for each year class as follows:

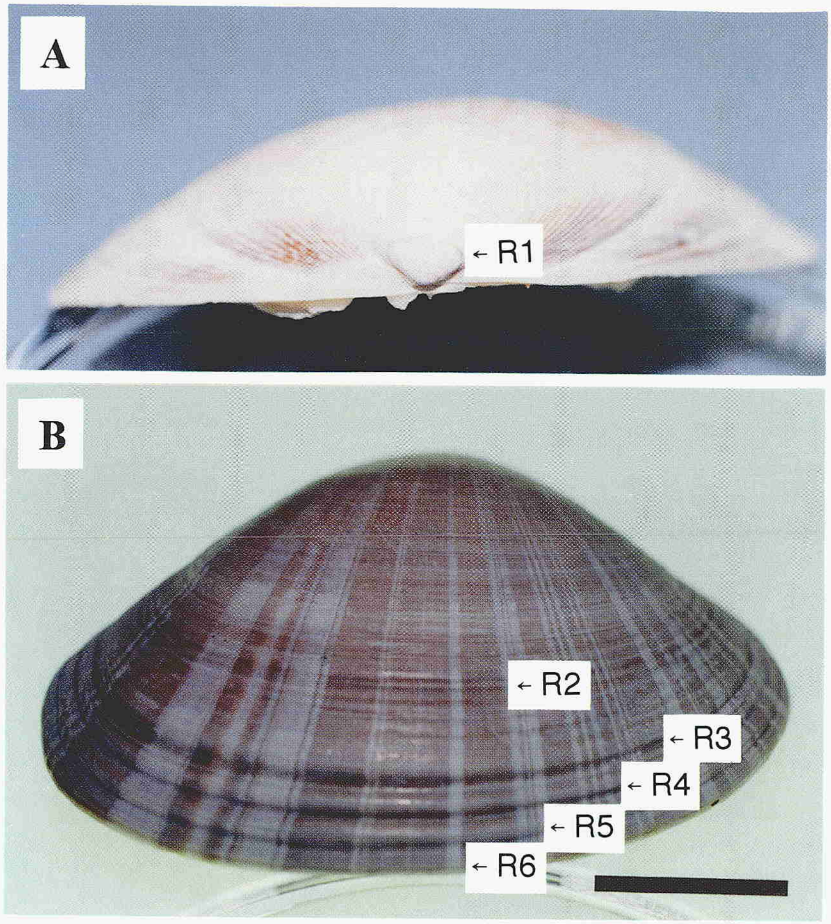

Figure 2
Mactra chinensis. Dorsal view (**A**) and outside view (**B**) of the right valve of a clam from Tomakomai in June 1992. R_n (n=1–6) indicates the nth external growth ring with a light penetrable band as clear rings could be distinguished from other innumerable fine rings. Scale bars represent 20 mm length.

$$N_{pi} = A\left\{\sum_{t=tc}^{t_{\lambda-1}} n_{t,i-1} S_t W_{t+1} + n_{0,i-3} S_{0-tc} W_{tc}\right\} \times 10^{-6} \quad (3)$$

where n_t = density (ind./m^2) at age t;
$t_{c,}$ = age at first capture; and
t_λ = longevity.

Although *M. chinensis* attains a commercial size at age 2.3 yr (i.e. in November of the second year) at Tomakomai (Sakurai, 1993), we assumed t_c to be 2.7 yr (i.e. in April of the second year) because the real stock size and the age composition in this study were investigated during April. S_t represents the survival rate at age t and was calculated from the following equation:

$$S_t = 1 - 100^{-1} m_t, \quad (4)$$

where m_t is the annual mortality rate at age t (age 0 yr: 94.0%; 1 yr: 53.1%; 2 yr: 44.8%; 3–9 yr: 42.7%) calculated with data from Sakurai (1996) with the assumption that annual mortality is constant. In April 1992–97, n_t was estimated in turn by multiplying the previous year by each S_t and by adding density of recruitment which was estimated by multiplying each $n_{0,i-3}$ by S_{0-tc}. Density at age 10 yr and older ($n_t \geq 10$) was not considered in the estimated age composition because the longevity (t_λ) of *M. chinensis* is 10 yr (Sakurai, 1993). The weight at age [t+0.7] yr, W_t, was calculated according to Equation 1 and the following equation from Sakurai (1993) :

$$L = 78.31\left\{1 - e^{-0.67(t-0.34)}\right\}, \quad (5)$$

where L = shell length (mm); and
t = age (years) of *M. chinensis*.

Results

The densities of newly settled juveniles, as shown in Figure 3, ranged from 1.3 to 157.0 ind./m^2 in 1987–94. The densities and the measured stock size of harvestable-size clams ranged from 0.7 to 3.1 ind./m^2 and from 249.8 to 1127.4 tons in 1987–94, respectively (Fig. 4).

The age composition of sunray surfclam in April 1991 is shown in Figure 5. The 2-year age group predominated with a share of 33.9%; the 6-, 7- and 3-year groups accounted for 17.3%, 12.2%, and 11.1%, respectively, and the other age groups represented less than 10% of the whole composition. Clams older than 9 years were not found in the survey area. The predicted stock size at each age in April 1992–97 calculated from Equation 3 is shown in Figure 6. It was predicted that the age groups spawned in 1988 and 1991 would predominate from age 2 to 5 in the harvestable-size clams.

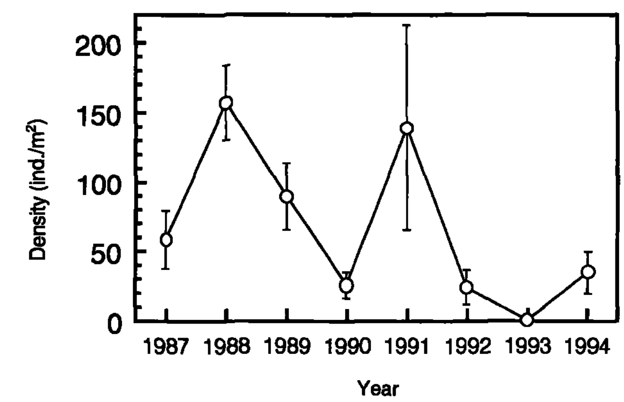

Figure 3
Annual fluctuation of the mean density of newly settled juvenile sunray surfclams. Vertical bars represent standard deviations.

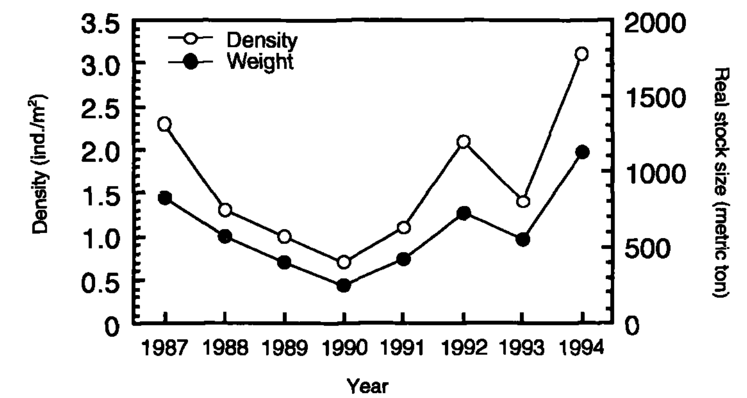

Figure 4
Annual fluctuation of the density (open circles) and the measured stock size (solid circles) of sunray surfclams.

Although bivalve fishing was prohibited in 1985–91 at depths of 5 to 10 m off the coast of Tomakomai, including the survey area, in order to protect *P. sachalinensis* juveniles, fishing resumed there in July 1992. Therefore, the catch of *M. chinensis* from 1992 to 1994 in the survey area was estimated by multiplying the annual catch at Tomakomai (Hokkaido, 1994, 1995, 1996) by the ratio of the survey area to the whole fishery area (Table 2). Subsequently, stock size was estimated by subtracting the value of the survey area in Table 2 from the sum of the age composition in Figure 6. The results are shown in Figure 7 together with the real stock sizes from Figure 4. The predicted values were within about 10% of the real values (Table 3).

Discussion

It is well known that marine invertebrates with planktonic larval stages show considerable fluctuations in numbers of recruits; sudden increases in numbers of juveniles occur occasionally (Hanaoka, 1972). Nakaoka (1993) noted that it is necessary for these populations to experience such sudden increases in order to maintain their populations. Sudden increases of *M. chinensis* have been reported from many of the fishing grounds in Japan. For example, a maximum density of about 980 ind./m^2 for clams with 60-mm-long shells was reported off the coast of Miura, Kanagawa Prefecture (Inoue and Ozu, 1960). In the present study, densities of newly settled juveniles ranged from 1.3 to 157.0 ind/m^2 (Fig. 3); during our study we did not find such a remarkable fluctuation in recruitment off the coast of Tomakomai compared with that observed for the population off Miura. Additionally, there were no dominant or vacant age groups in the age composition (Fig. 5); thus, it appears that the population of *M. chinensis* is maintained by comparatively stable recruitment occurring off the coast of Tomakomai.

Mactra chinensis grows to harvestable size at age 2.3 yr at Tomakomai (Sakurai, 1993); consequently newly settled juveniles spawned in the years 1987 through 1991 are presumed to have recruited to the stock in April 1990–94. As Figures 3 and 4 show, juvenile densities in 1988, 1989, and 1991 were relatively high, causing the real stock sizes in 1991, 1992, and 1994 to increase in comparison with each previous year. In contrast, the lower juvenile densities in 1987 and 1990 caused the real stock size in 1990 and 1993 to decrease in comparison with each previous year. Therefore, it is suggested that the population dynamics at Tomakomai are directly influenced by the number of newly settled juveniles. The number of juveniles is determined by the settlement and mortality of early benthic stages (Günther, 1992). We think that it is necessary to examine the factors that cause fluctuations in the number of juveniles to gain a full understanding of the population dynamics of *M. chinensis*.

In the present study, we define a model using two known population parameters, juvenile density and age compositions, to predict the stock size of *M. chinensis*. It has been shown that the age groups that have relatively higher densities at the juvenile stage predominate for four years from age 2 to 5 in harvestable-size clams. Saito et al. (1982) reported that a large catch of *M. chinensis* continued for a few years off the coast of Ishikari, Hokkaido, because the dominant age group was maintained. This was the case in our study. Therefore, we consider that our model is appropriate for predicting the population dynamics of *M. chinensis* at Tomakomai and other sites. Furthermore, the predicted stock size of our model was close to the measured value (Fig. 7), and consequently accurate long-term prediction of stock size is possible with this model, provided age composition and juvenile density are determined.

On the other hand, analysis of age and growth based on external growth rings has been conducted for various bivalves including *Placopecten magellanicus* (e.g. Stevenson and Dickie, 1954; Claereboudt and Himmelman, 1996), *Pecten maximus* (e.g. Dillon and Clark, 1980), *Megangulus venulosus* (Goshima et al., 1991), *Mesodesma mactroides* (Defeo et al., 1992), *Clinocardium californiense* (Goshima and Noda, 1992), and *Abra tenuis* (Dekker and Beukema, 1993). However, it is suggested that age determination based on external growth rings of bivalves would be unreliable because it is difficult to distinguish the growth rings from other rings owing to several stimuli (Dillon and Clark, 1980). Nevertheless, the growth rings of *M. chinensis* have been distinguished clearly from other innumerable fine rings by checking the rings with light penetrable bands (Sakurai, 1993). These bands are regarded as nacreous layers. Therefore, age determination in the present study would be as reliable as that based on microgrowth analysis with acetate peels or thin sections (Lutz and Rhoads, 1980), and we consider that our model would be able to predict the stock size without over- or underestimates. In our model, however, annual mortality is assumed to be constant; therefore, age com-

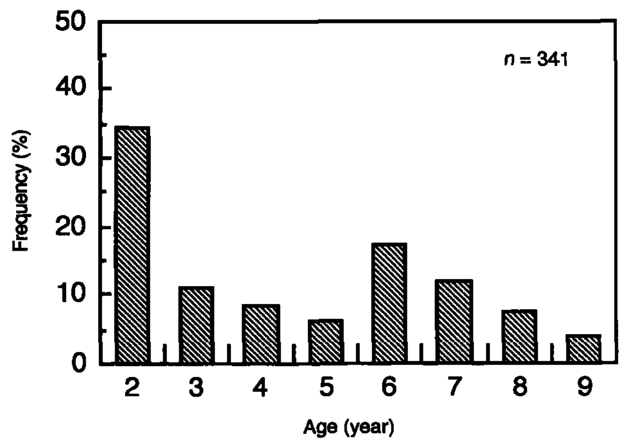

Figure 5

Age composition of the harvestable-size sunray surfclams sampled at station N (Fig. 1) in April 1991.

Table 2

Estimated catch of *M. chinensis* in the survey area and whole fishery ground off the coast of Tomakomai.

	Catch (metric ton)	
Year	Survey area	Whole fishery ground[1]
1992	7.2	36.0
1993	14.6	73.0
1994	22.0	108.0

[1] Based on data from Hokkaido Fisheries Statistics in 1994, 1995, and 1996.

Table 3

Comparison of the real (R) and predictive (P) stock size for *M. chinensis*.

Year	R (metric ton)	P (metric ton)	$(R-P) \times 100/R$ (%)
1992	728.3	651.8	10.5
1993	550.3	586.0	–6.5
1994	1,127.4	1,015.8	9.9

position would need to be reinvestigated if there was an unexpected change in mortality, such as that resulting from clams being washed ashore by a large typhoon or other storms (Sakurai et al., 1996).

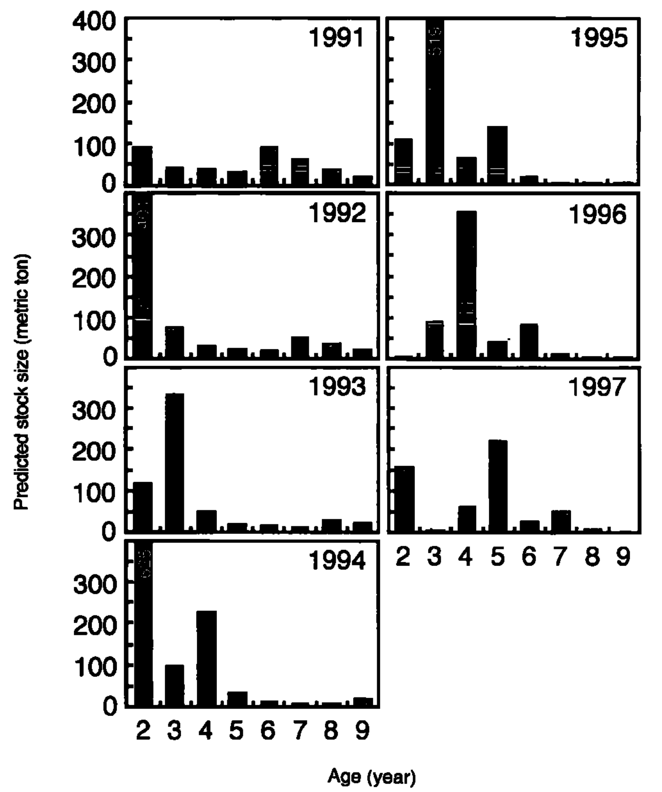

Figure 6
Predicted age compositions for the harvestable-size sunray surfclams in April from 1991 to 1997.

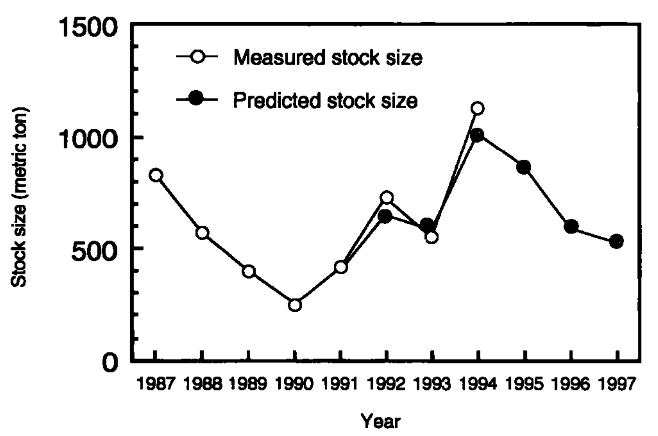

Figure 7
Annual fluctuation of the measured (open circles) and predicted (solid circles) stock size of sunray surfclams.

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