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Potential Use of Extremely High Biomass and Production of Copepods in an Enclosed Brackish Water Body in Lake Nakaumi, Japan, for the Mass Seed Production of Fishes

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[2]Faculty of Life and Environmental Sciences, Shimane University, Matsue 690-8504, Japan Tel: 81-852-326582. Fax: 81-852-326598. E-mail: aizaki@life.shimane-u.ac.jp

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Shin-ichi Uye, Shinobu Nakai and Moriyuki Aizaki (2004) Potential use of extremely high biomass and production of copepods in an enclosed brackish water body in lake Nakaumi, Japan, for the mass seed production of fishes. *Zoological Studies* **43**(2): 165-172. We found extremely high abundance, biomass, and production rates of mesozooplankton in an enclosed brackish water body (called the Honjo District) in Lake Nakaumi, Japan, during a 2-yr investigation. To the best of our knowledge, the overall biomass mean of 71.0 mg C m^{-3} is one of the highest values recorded so far anywhere in the world. Copepods dominated the zooplankton community in terms of abundance (94.4%) and biomass (83.4%). Zooplankton biomass and production rates were twice as high in Honjo District as those in adjacent Lake Nakaumi, although the phytoplankton chlorophyll α concentration was twice as low. Two reasons for the enhanced zooplankton standing stock in Honjo District might be the development of weak benthic deoxygenation and lower numbers of planktivorous fish. We propose to use zooplankton as a food source for the intensive mass seed production of finfish. By our conservative estimate, exploiting 10% of the daily zooplankton production (or around 2.5% of the biomass) of Honjo District would allow the production of 5.6 million red sea bream (*Pagrus major*) or Japanese flounder (*Paralichthys olivaceus*) seeds, and 15.4 million ayu (*Plecoglossus altivelis*) seed fish annually.
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Key words: Brackish water ecosystem, Lake Nakaumi, Eutrophication, Mass seed production of fish, Economic value.

Brackish waters, such as estuaries, salt marshes, and mangrove swamps, are recognized as ecosystems with the highest biological production among aquatic ecosystems, owing to high nutrient inputs from the adjacent land and rivers (i.e., Odum 1971). These areas are not only productive fish and shellfish fishery grounds, but also habitats for many migrating water bird species. From these aspects, brackish waters can be regarded as important ecosystems to be preserved. However, in Japan, the major coastal brackish lakes, such as Lake Kasumigaura and Lake Hachirogata, have been desalinated and/or reclaimed for agricultural and/or industrial purposes, and approximately 40% of such lake areas have been reclaimed in the past few decades (Hirai 1993). The perceived higher economic value of newly reclaimed land compared to the original water body has been the major reason that many people favor reclamation. In accordance with increased public awareness of the ecological importance of brackish water ecosystems and environmental deterioration occurring therein, more attention is now being paid to preserving these productive ecosystems.

Two estuarine lagoons, Lake Shinji (with an area of 79.2 km^2 and an average depth of 4.5 m) and Lake Nakaumi (with an area of 86.8 km^2 and

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an average depth of 5.4 m), and a short connecting river (with a length of 7.3 km) between the 2 lakes, the Ohashi River, constitute the largest brackish water ecosystem remaining in Japan at present (Fig. 1). Fresh water from the Hii River and other small streams and saltwater through the Sakai Strait (with a length of 7.5 km, and a width of 0.3 km) meet and mix in this area, providing oligohaline to polyhaline salinity gradients (Okuda 1997). Due to both limited water exchange between Miho Bay and Lake Nakaumi and increased load of nutrients and organic matter from urban sewage and agricultural fields, this lagoonal system has become highly eutrophic. The formerly productive ecosystem has been considerably deteriorated, particularly in Lake Nakaumi, as manifested by frequent phytoplankton blooms and the concomitant formation of benthic anoxia (Ohtake et al. 1982, Kondo et al. 1990). Lake Shinji, in contrast, continues to sustain a dense population of the commercial filter-feeding bivalve (*Corbicula japonica*), whose annual harvest is around 8000 t wet weight with the shell (Nakamura 1998).

In the 1970s, there was a plan to reclaim the northwestern part of Lake Nakaumi (called the Honjo District, with an area of 16.2 km^2, an average depth of 5.1 m, and a water volume of 8.25 x 10^7 m^3) for agricultural use, and consequently the district was enclosed by construction of a bank in 1981. The water exchange between Honjo District and Lake Nakaumi per se is limited to that which occurs through a narrow waterway along the western shore. Although fisheries, mainly by set nets, are being operated, the landings were extremely reduced after the embankment was built.

The first objective of this paper was to clarify the biological production of mesozooplankton, the major secondary producers which graze on phytoplankton and prey upon by planktivorous fish and carnivorous invertebrates, in Honjo District. We conducted a monthly investigation to measure mesozooplankton abundance, biomass, and production rates during 2 yr at 7 sampling stations in Honjo District, in addition to a station in adjacent Lake Nakaumi (Fig. 1). If the potential exists to mass-produce mesozooplankton in Honjo District, we would like to propose a plan to use this enclosed brackish area as a site for intensive fish seed production. This would increase the economic potential of this water body, and this has never been done before. Hence, our second objective was to assess the feasibility of this plan.

MATERIALS AND METHODS

We visited 7 stations in Honjo District (stns. 1 to 7, with depths of 3-9 m) and a station (stn. 8, with a depth of 5 m) in Lake Nakaumi monthly during 2 yr from June 1997 to May 1999 using the boat Gobius of Shimane University (Fig. 1). At each station, vertical profiles of temperature, salinity, and dissolved oxygen concentrations were determined at every 1 m interval with a water meter (Horiba, U-10). Water samples were taken with a Van Dorn water bottle from depths of 0.5, 4.0, and 6.0 m, and 50 ml of the water was filtered

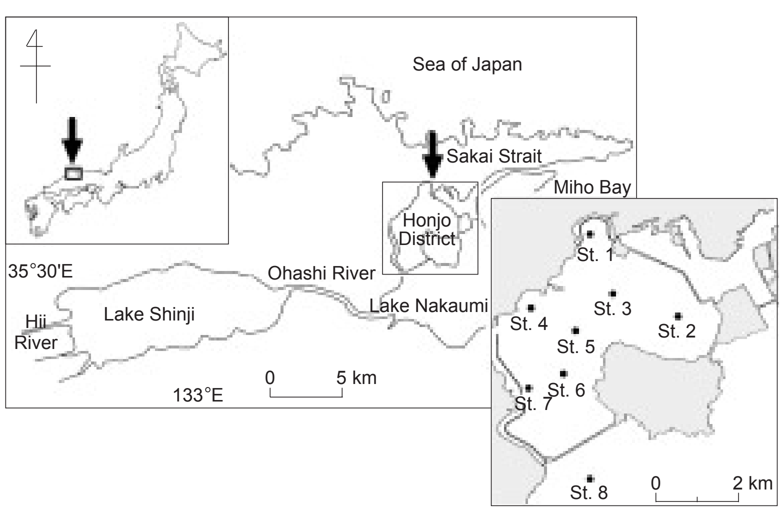

Fig. 1. Map of the Lake Shinji, Ohashi River, and Lake Nakaumi brackish water system, with the location of sampling stations in Honjo District, an enclosed water body, and in Lake Nakaumi.

onto glassfiber (Whatman GF/F) filters. Chlorophyll α concentrations of these seston samples were determined fluorometrically (Turner Designs, Model 10) after extraction in N,N-demethylformamide. Mesozooplankton samples were collected with vertical hauls of a plankton net (with a mouth diameter of 0.225 m, a length of 1 m, and a mesh size of 100 μm) fitted with a flow meter (Rigosha Co.) from the bottom to the surface. Plankton samples were immediately fixed with 5% buffered formalin.

Zooplankton samples were split into 1/2 to 1/128 portions, depending on the density of organisms, with a Motoda box splitter. From these subsamples, at least 200 specimens were identified and counted under a stereoscopic binocular microscope. Copepods (except for Harpacticoida), cladocerans, appendicularians, and chaetognaths were identified to the species or genus level, while other taxa, such as malacostracans and larvae of various benthic animals, were classified to higher taxonomic levels. Their appropriate body dimensions (see Uye 1982) were measured using a video micrometer (Olympus, VM-10), and automatically converted, using a personal computer, to carbon weights using predetermined length-weight regressions (see Uye and Shimazu 1997 for details).

The production rate of each taxonomic group (P, mg C m^{-3} d^{-1}) was estimated based on its biomass (B, mg C m^{-3}) and an empirically-determined potential (or maximum under non-food limitation) specific growth rate (g, d^{-1}): $P = B \times g$. The specific growth rates of copepods and appendicularians in relation to temperature have previously been determined for species mainly from the Inland Sea of Japan (see table 1 of Uye and Shimazu 1997). For *Acartia sinjiensis*, the following equation to express a relationship between growth rate and temperature (T, °C) was used: $g = 0.022\exp(0.032T)$ (Uye and Fujinaka, unpubl. data). We assumed that *Pseudodiaptomus inopinus* has a similar growth rate-temperature relationship to the congener, *P. marinus*. For the remaining taxa (e.g., cladocerans, malacostracans, chaetognaths, and benthos larvae), Ikeda-Motoda's physiological method was applied (Ikeda and Motoda 1978; Omori and Ikeda 1984).

RESULTS

Environmental variables

Since environmental variables were very similar among the 7 stations in Honjo District, we chose stn. 3 as a representative of this area. Seasonal variations at the surface (i.e., 0.5 m) and

Table 1. Comparison of annual mean biomass and production rates of mesozooplankton among various estuarine and coastal marine waters

Location	Biomass (mg C m^{-3})	Production rate (mg C m^{-3} d^{-1})	Reference
Fukuyama Harbor, Japan	39.1	6.85	Uye and Liang 1998[1]
Inland Sea of Japan, Japan	20.0	2.83	Uye and Shimazu 1997
Honjo District, Japan	47.4	-	Uye et al. 2000
	71.0	17.6	This study
Lake Nakaumi, Japan	37.3	-	Uye et al. 2000
	32.2	7.7	This study
Lake Shinji, Japan	80.2	-	Uye et al. 2000
Long Island Estuary, USA	33.2	-	Turner et al. 1983
Narragansett Bay, USA	28.0	-	Hulsizer 1976
	-	27.3-32.1	Durbin and Durbin 1981[2]
Jakle's Lagoon, USA	-	9.0	Landry 1978[3]
New Port Estuary, USA	21.5	-	Fulton 1984[1]
Nueces Estuary, USA	16.8	-	Buskey 1993
Westershelde Estuary, The Netherlands	35.5	4.4	Escaravage and Soetaert 1995

[1]For copepods only.
[2]For *Acartia hudsonica* and *A. tonsa* from March to December.
[3]For *Acartia clausii*.

the bottom (i.e., 6.0 m) are shown in fig. 2, together with those at stn. 8 in Lake Nakaumi for comparison. Both stations showed similar temperature fluctuations of from around 6 to 29°C, but thermal stratification was more prominent at stn. 8. Salinity was vertically much more homogeneous at stn. 3 (with means of 14.7 and 16.7 psu at the surface and bottom, respectively) than at stn. 8 (with means of 14.3 and 24.6 psu, respectively). At the latter station, the surface salinity dropped to as low as 2.9 psu. Dissolved oxygen concentrations were usually oversaturated at the surface, while deoxygenation at the bottom was prominent, particularly at stn. 8 during summer and fall. Chlorophyll α concentrations were much lower (with means of 4.7 and 3.0 μg l^{-1} at the surface and bottom, respectively) at stn. 3 than at stn. 8 (with means of 9.6 and 6.3 μg l^{-1}, respectively). At the latter station, 2 large chlorophyll peaks in September 1997 and April-May 1998 were caused by blooms of the dinoflagellate, *Prorocentrum minimum*.

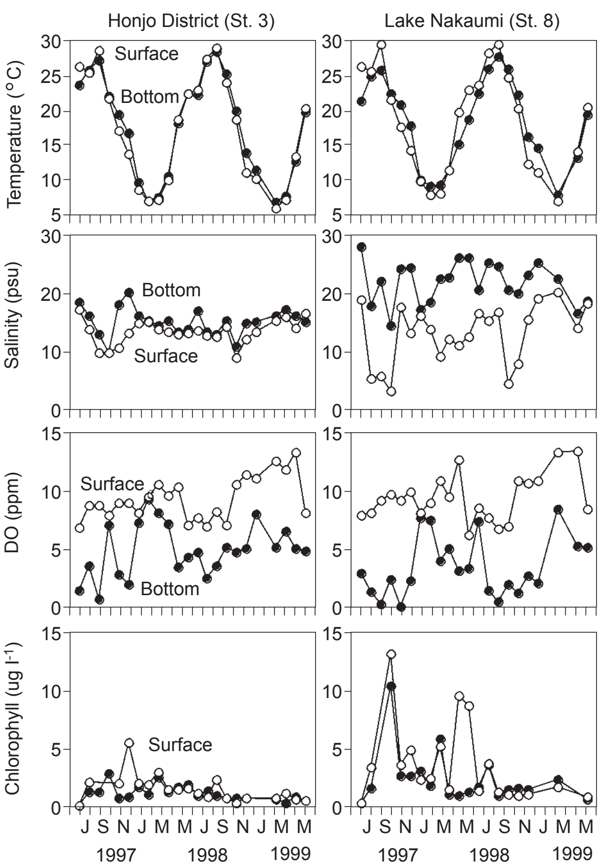

Fig. 2. Comparison of monthly changes in temperature, salinity, dissolved oxygen concentrations, and chlorophyll α concentrations at the surface (●) and the bottom (○) between Honjo District (stn. 3) and Lake Nakaumi (stn. 8).

Mesozooplankton abundance

Mesozooplankton abundance was higher and showed greater fluctuations with time in Honjo District than in Lake Nakaumi (Figs. 3, 4). The regional variation within Honjo District was not so large, since the coefficient of variation (CV) around the means for the 7 stations was usually < 50%. The abundance showed a biannual cycle, with a large peak in fall and a small peak in early summer, although this pattern was less apparent in the second half of the study period. The density varied from 2.59 x 10^4 individuals m^{-3} in Apr. 1999 to 115.9 x 10^4 individuals m^{-3} in Nov. 1997, with an overall mean of 37.2 x 10^4 individuals m^{-3}. In Lake Nakaumi, the overall mean abundance was 18.4 x 10^4 individuals m^{-3}, and ranged from 1.9 x 10^4 individuals m^{-3} in Sept. 1997 to 52.9 x 10^4 individuals m^{-3} in May 1998 (Fig. 4).

In both water bodies, copepods absolutely dominated the mesozooplankton community (with means of 94.4% in Honjo District and 93.9% in Lake Nakaumi; Figs. 3, 4). The occurrence of mesoplankton was significant in summer. Bivalve larvae were more abundant in Honjo District, while polychaete larvae were more notable in Lake Nakaumi. Copepods showed a similar seasonal occurrence in both areas. The small cyclopoid copepod, *Oithona davisae*, dominated except in winter, when *Eurytemora pacifica* and *Acartia hudsonica* occurred more abundantly. In summer, another *Acartia* species (*A. sinjiensis*) occurred. *Sinocalanus tenellus* and *Pseudodiaptomus inopinus* occurred rather irregularly; the former species was more important in Lake Nakaumi.

Mesozooplankton biomass and production rate

Unlike the seasonal variation in abundance, the biomass showed an annual peak in winter (Figs. 5, 6). It changed from 9.9 to 373.2 mg C m^{-3} in Honjo District and from 5.0 to 151.8 mg C m^{-3} in Lake Nakaumi. The overall mean biomass was 71.0 mg C m^{-3} in Honjo District, which was double that in Lake Nakaumi (at 35.4 mg C m^{-3}). On average, copepods accounted for 83.4% and 82.1% of the mesozooplankton community biomass in Honjo District and Lake Nakaumi, respectively, although in summer mesozooplankton biomass exceeded copepod biomass. The contribution of *O. davisae* became less important in terms of biomass due to its small body size. In winter, *A. hudsonica* and *E. pacifica* accounted for > 50% of the mesozooplankton biomass. A large biomass peak in Mar.

1999 was attributed primarily (around 95%) to *E. pacifica*.

Due to the reflection of a positive temperature effect on the specific growth rate, the production rate of mesozooplankton was computed to be higher in spite of lower biomass in summer (Figs. 5, 6). The higher winter production rate was due to extremely higher biomass. The overall mean production rate was 17.6 mg C m^{-3} d^{-1} (with a range of 1.2 to 51.6 mg C m^{-3} d^{-1}) in Honjo District and 9.1 mg C m^{-3} d^{-1} (with a range of 0.9 to 32.2 mg C m^{-3} d^{-1}) in Lake Nakaumi.

DISCUSSION

Characteristics of zooplankton in Honjo District

Previous studies (Miyadi 1962, Uye et al. 2000) demonstrated that the brackish water system of Lake Shinji, Ohashi River, and Lake Nakaumi generally harbored mesozooplankton at a high density, although there were remarkable variations with season (e.g., in temperature) and location (e.g., in salinity). As previously observed by Ohtsuka et al. (1999) and Uye et al. (2000), the present study also demonstrated significantly higher mesozooplankton abundance and biomass in Honjo District than in Lake Nakaumi, whereas the taxonomic composition was similar. The following environmental properties for Honjo District, compared to adjacent Lake Nakaumi, were apparent: 1) the water column was vertically more homogeneous, 2) salinity was seasonally more stable, 3) benthic deoxygenation was less significant, and 4)

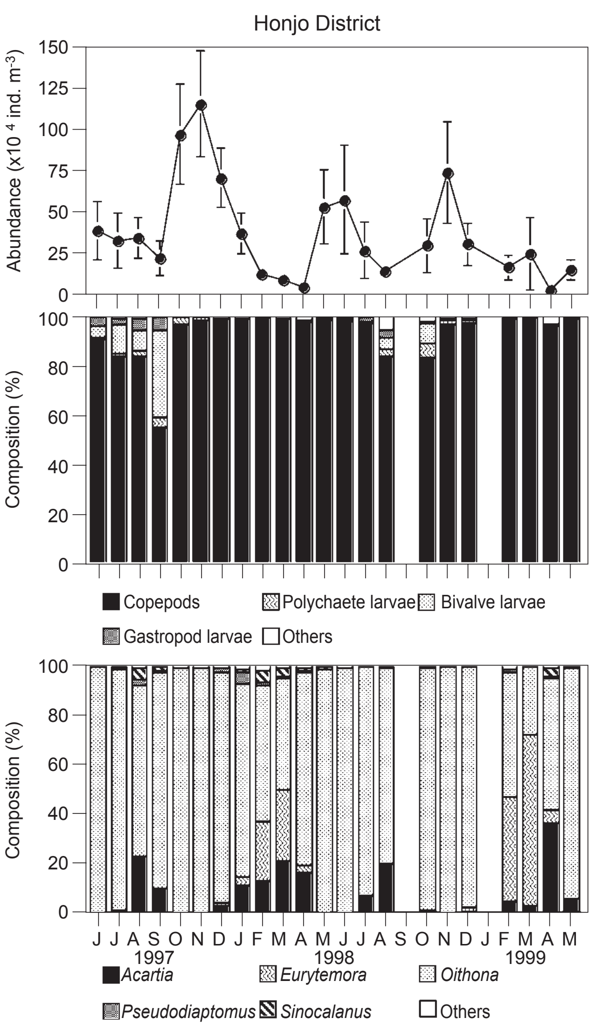

Fig. 3. Monthly changes in mesozooplankton abundance (top), higher taxonomic composition (middle), and copepod genus composition (bottom) in Honjo District. Values are the mean for 7 stations. Vertical lines denote the SD.

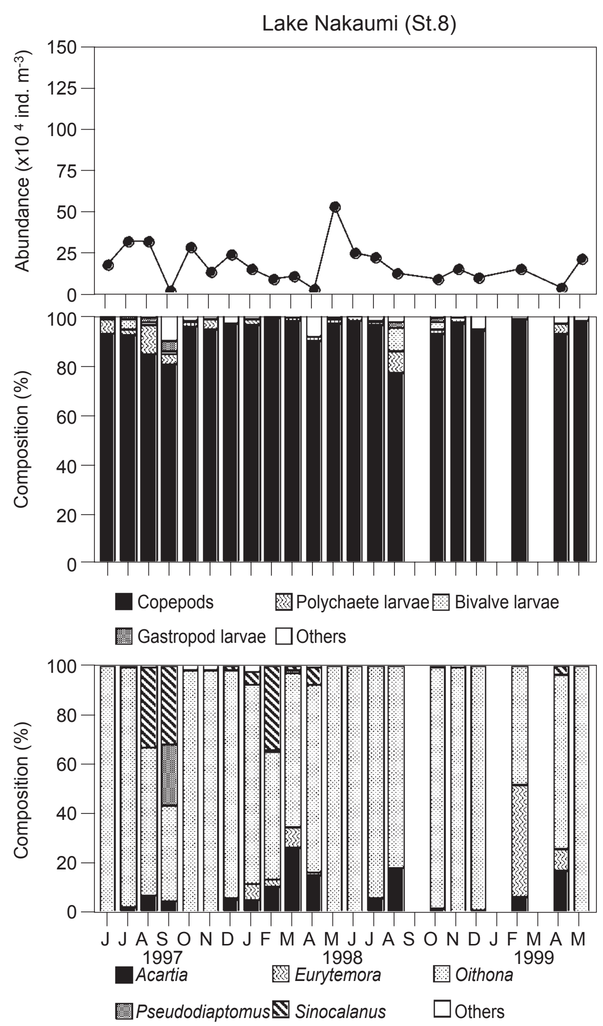

Fig. 4. Monthly changes in mesozooplankton abundance (top), higher taxonomic composition (middle), and copepod genus composition (bottom) in Lake Nakaumi.

the phytoplankton biomass was lower.

In spite of the lower phytoplankton biomass, the zooplankton biomass and production rate were twice as high in Honjo District compared to those in Lake Nakaumi. One of the reasons for such a phenomenon might be the less-developed benthic anoxic layer in Honjo District. Adult copepods (e.g., *Acartia tonsa* and *Oithona colcarva* from Chesapeake Bay, USA) die at oxygen concentrations < 1-2 ppm (Roman et al. 1993), and they actually avoid deoxygenated depths in Lake Nakaumi (Harada et al. 1985). Thus, lesser-developed deoxygenation in the water mass provides copepods with wider habitat space in Honjo District, compared to Lake Nakaumi. Deoxygenation also causes a lower recruitment rate in copepods through inhibitive hatching of their eggs which accumulate near or on the bottom (Uye 1980, Roman et al. 1993, Marcus et al. 1994). This mechanism, however, does not work for the egg-sac-carrying *O. davisae* (Uye 1994), which was actually outnumbered in both areas.

Another reason for the higher zooplankton biomass in Honjo District might be lower abundance of planktivorous fish (e.g., *Harengus zunasi*, *Englauris japonica*, and *Hemiramphus sajori*). Larvae and juveniles of these fish species immigrate from Miho Bay, the Sea of Japan, in spring to early summer and dwell in this food-rich brackish system until they emigrate back in late fall (Miyadi 1962). Accordingly, the amount of fish caught by set nets in Honjo District was high in summer and fall and low in winter and spring (Koshikawa 1999, Ishitobi et al. 2000), indicating higher predation pressure by fish in warmer seasons. However, the annual fish catch by set nets (collected once per month) in Honjo District (46 kg) was much lower than that in Lake Nakaumi (130 kg) (Ishitobi et al. 2000), due to less immigration of fish populations into the enclosed Honjo District.

Strictly speaking, comparisons of zooplankton biomass and production rates among different studies are often difficult, since collecting gear (particularly mesh size of the plankton net), techniques, times, and methods for estimating the production rate differ from one study to another. Table 1 compares the annual mean biomass and production rates of zooplankton collected by 100- to 200-μm-mesh nets. Among various estuarine and coastal marine waters, Honjo District harbors extraordinarily high zooplankton biomass. The only exception is Lake Shinji, the inner lake of this brackish system. Production rate in Honjo District is highest at least among published values for Japanese estuarine and coastal waters, where the same method was employed to estimate the production rate (Uye and Shimazu 1997, Uye and Liang 1998, this study).

How many fish seeds can be produced in Honjo District?

Extremely high mesozooplankton biomass and production in Honjo District stimulated us to propose using them as food for the mass seed production of economically important finfishes. An extensive seed production method, namely stocking fish larvae at low densities in large, outdoor earthen ponds (see Ohno 1991), is inappropriate here for marine fishes, due to the low salinities. Our proposed plan is an intensive system, for which a hatchery needs to be constructed on the bank between Honjo District and the outer area connecting Sakai Strait (with salinities of > 25 psu), with indoor concrete tanks as adopted by many sea-farming stations in Japan. Facilities are

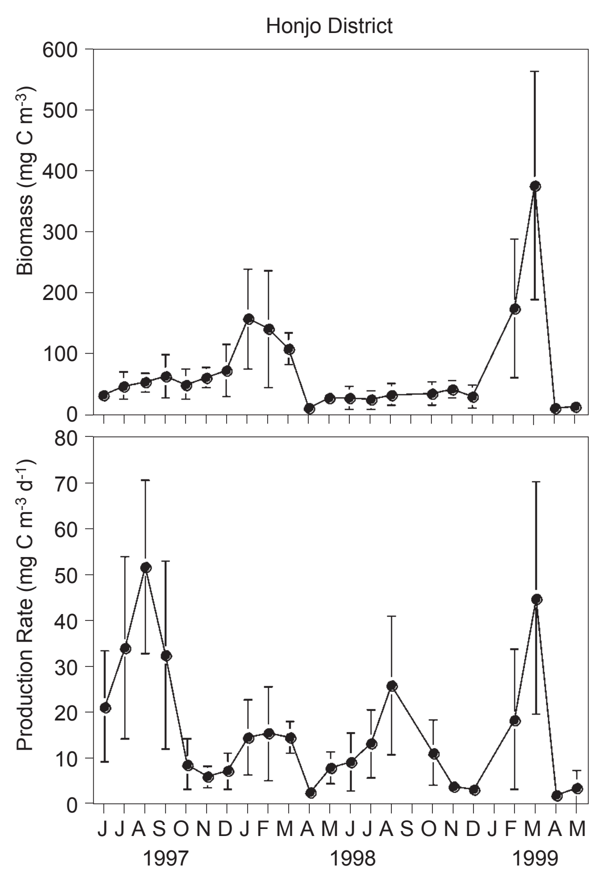

Fig. 5. Monthly changes in mesozooplankton biomass and production rate in Honjo District. Values are the mean for 7 stations. Vertical lines denote the SD.

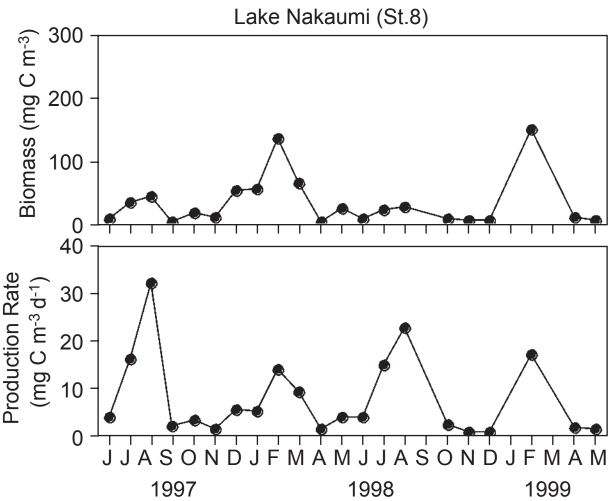

Fig. 6. Monthly changes in mesozooplankton biomass and production rate in Lake Nakaumi.

also needed in which to collect large amounts of zooplankton, like light traps or large streamer-like plankton nets, and deliver them by pumping to each rearing tank.

Red sea bream (*Pagrus major*), the most common fish species used for intensive seed production in Japan, ingests mainly copepods during its larval stages from around 10- to 40 mm body length (Tanaka et al. 1987). According to Kitajima (1979), a larval red sea bream of 30 mm body length (around 390 mg wet weight), the target size for hatchery rearing, ingests about 250 mg wet weight of copepods daily. Using a wet-weight-to-carbon conversion of 0.1 for copepods (Hirota 1981), the daily food requirement is 25 mg C per fish. We assume that the overall mean biomass and production rate of mesozooplankton (i.e., 71.0 mg C m^{-3} and 17.6 mg C m^{-3} d^{-1}, respectively) can be attained in Honjo District (with a water volume of 8.25×10^7 m^3) throughout the seed production period (from May to July for red sea bream). If we exploit 10% of zooplankton production (about 2.5% of the biomass) daily, the harvest (1.45×10^5 g C) would be equivalent to the diet of 5.8×10^6 30-mm-long seed fish. This number is a minimum, since rearing populations usually consist of several cohorts. A similar procedure may also be applicable to Japanese flounder (*Paralichthys olvaceus*), whose seed production season largely overlaps that of the red sea bream (Takashima 1997).

Ayu (*Plecoglossus altivelis*) is also a species recommended for seed production. This diadromous fish spawns eggs in late fall in rivers, and hatched larvae are driven downstream to coastal marine waters to feed mainly on copepods until they migrate upstream in the river in spring and early summer. The seed production season is from Dec. to Feb. A larval ayu of 50 mm body length (around 800 mg wet weight), the target seed size, consumes 100 mg of wet weight of diet per day (Takashima 1997). As estimated similarly to that above, at least 14.5×10^6 seed fish of ayu could be produced.

Judging from the above estimates, our proposed plan to use Honjo District as a field for the mass production of seed fish of economically important species seems to be highly feasible. This plan would add new economic value to Honjo District, where currently set-net fisheries are being poorly operated by a few fishermen, and can be an option for the efficient utilization of this enclosed water body.

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Additional Notes

After our investigation, the Ministry of Agriculture, Fisheries and Forestry of Japan officially announced in 2000 to stop the reclamation of Honjo District, as a result of strong public criticism against this public work. However, it has not yet been decided whether or not the Honjo District embankment will be removed. We strongly recommend removal in order to enhance the water mixing in Lake Nakaumi, where benthic anoxia chronically takes place at present. If Honjo District remains as it is, this productive water body can be used for the mass seed production of economically important finfishes.