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Predation by diving ducks on the biofouling mussel *Musculista senhousia* in a eutrophic estuarine lagoon

Masumi Yamamuro[1,*], Nariko Oka[2], Jun'ichi Hiratsuka[3]

[1]Marine Geology Department, Geological Survey of Japan, 1-1-3 Higashi, Tsukuba, Ibaraki 3058567, Japan
[2]Yamashina Institute for Ornithology, Konoyama, Abiko, Chiba 2701145, Japan
[3]Shimane Research Group of Wild Life, c/o Dr. Iwao Sakamoto Department of Medicine, Shimane Medical University, 89-1 Enyamachi, Izumo, Shimane 6938501, Japan

ABSTRACT: The effect of predation by diving ducks (*Aythya fuligula*, *Aythya ferina*, and *Aythya marila*) on filter-feeding bivalves was evaluated in eutrophic estuarine lagoons, Lakes Nakaumi and Shinji, in Japan. Bivalves take up nutrients in the form of phytoplankton and detritus. Winter-migrating diving ducks feed on these bivalves during the cold season. In Lake Nakaumi, diving ducks chiefly consumed the biofouling mussel *Musculista senhousia*. The biomass of *M. senhousia* decreased markedly at most sampling points during duck wintering, averaging 1126 g m^{-2} (wet weight) at 42 sampling points in November 1996 and 24 g m^{-2} in March 1997 The amount of nitrogen in *M. senhousia* eaten by ducks during winter was estimated at 52 t and phosphorus at 3.8 t. In the absence of ducks, *M. senhousia* death in summer would add equivalent nitrogen and phosphorus loads to the lagoon. The decomposition of *M. senhousia* in summer when water mixing is weak would also accelerate oxygen depletion at the lagoon bottom. Mussel predation by wintering ducks would therefore decrease unfavorable effects of biofouling mussel decomposition in summer when nuisance phytoplankton blooms and anoxia occur easily.

KEY WORDS: Nitrogen · Phosphorus · *Aythya fuligula* · *Aythya ferina* · *Aythya marila* · *Musculista senhousia* · *Corbicula japonica* · Lake Nakaumi · Lake Shinji

INTRODUCTION

Aquatic birds are top-level consumers in many shallow-water areas, feeding largely on fish and macroinvertebrates. Because of the large biomass and enormous population, they may alter the standing crop of prey and play an important role in nutrient flux (Erwin 1996).

Most duck species depend almost exclusively on shallow-water habitats. Increased human activity in coastal areas generally reduces the use of shallow-water areas by duck species. The wintering place for diving ducks in the Nakdong River Estuary, Korea, for example, was lost during the 1980s because of barrage and reclamation projects (Doornbos et al. 1986, Kim & Won 1994). The diving duck population in the U.S. also decreased, presumably because of human impact (Perry & Deller 1996).

Three species of diving ducks—*Aythya fuligula* (tufted duck), *Aythya ferina* (pochard), and *Aythya marila* (scaup)—winter in the eutrophic estuarine lagoons of Lake Nakaumi (area 86.8 km^2, mean depth 5.4 m) and Lake Shinji (area 79.2 km^2, mean depth 4.5 m) in Japan. The diving duck population is generally more than 5 times larger in Lake Nakaumi than in Lake Shinji. Based on data counted on the day of the nationwide New Year's bird count in Japan, the average population and standard deviation of *Aythya* spp. in the period 1986 to 1995 was 50276 ± 14493 in Lake Nakaumi and 8744 ± 2115 in Lake Shinji (Wild

*E-mail: yamamuro@gsj.go.jp

Bird Society of Japan, Shimane Prefecture Branch unpubl.). Both lakes are similarly eutrophic. Total nitrogen concentration is 400 to 550 µg l^{-1} in both lagoons. The total phosphorus concentration is 30 to 50 µg l^{-1} in Lake Shinji and 40 to 65 µg l^{-1} in Lake Nakaumi (Kato et al. 1996). Shallow basin areas where bivalves, the ducks' main food source, survive are similar.

In Lake Nakaumi, the most dominant macrobenthos is the biofouling Asian mussel *Musculista senhousia* (Sawamura et al. 1993); the infaunal commercial clam *Corbicula japonica* dominates in Lake Shinji (Nakamura et al. 1988). *M. senhousia* is a thin-shelled mytilid that lives in the intertidal and subtidal soft sediments of bays and estuaries, where it weaves a cocoon by binding sediment with its byssal threads. Where the mussel lives in high densities, these cocoons are woven together to create a byssal mat, thereby altering the nature of the sediment inhabited by commercial infaunal bivalves. Since neither *M. senhousia* nor *C. japonica* survives in anoxic conditions, their distributions are restricted to the shallower parts of each lagoon (Nakamura et al. 1988, Sawamura et al. 1993). These bivalves are probably the chief prey of diving ducks.

Such predation would contribute to the removal of biofouling mussels from the lagoon. Several studies have shown that bivalves are the most important food source for wintering diving ducks (e.g. Stańczykowska et al. 1990, De Vaate 1991). The effect of predation, however, may not significantly alter the bivalve biomass (Sewell 1996, Hilgerloh 1997). Nitrogen and phosphorus contributed by aquatic birds may degrade lagoon water quality (Manny et al. 1994, Marion et al. 1994).

Our purpose was to (1) examine the importance of bivalves as duck prey, (2) estimate the number of biofouling mussels removed by ducks through predation, and (3) deduce the possible effects of mussel predation by ducks on lagoon water quality.

METHODS

Duck diet and nutrient concentrations. We collected dead *Aythya fuligula*, *A. ferina*, and *A. marila* accidentally caught in fisheries' gill nets in Lake Nakaumi and Lake Shinji (Fig. 1) between October 1994 and March 1995, and examined duck nitrogen and phosphorus concentrations, whole body and gizzard weight, and digestive organ content. Gill nets were usually set for half a day, and drowned ducks found when nets were taken in were immediately frozen until dissected. Gender was identified by genitalia. Digestive organ content was removed and fixed with buffered formalin (10%) for later identification. The weight of content

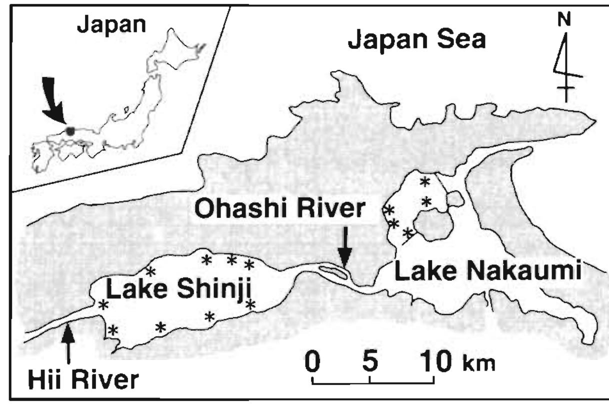

Fig. 1. Location of Lakes Nakaumi and Shinji (Japan). (*) Locations of gill nets

was subtracted from the whole body weight of ducks. Pectoral muscle, liver, and the whole body (excluding feathers, wing/leg bones, head, and intestine) of ducks were freeze-dried, powdered using a mill, and analyzed for nitrogen and phosphorus.

Bivalve nutrient concentrations and caloric values. Organic carbon, nitrogen, and phosphorus concentrations and weight of *Musculista senhousia* sampled at the east end of the Ohashi River (Fig. 1) were determined monthly from October 1994 to March 1995. To determine caloric values, *M. senhousia* and *Corbicula japonica* were sampled at the east end of the Ohashi River in October and November 1994 and the north shore of Lake Shinji in March 1995.

Bivalves were sampled with a Smith-McIntyre grab sampler (22 × 22 cm^2) and sieved in a nylon bag (mesh: 0.5 mm) on the boat. They were rinsed quickly with deionized water in the laboratory, selected randomly for weighing, and freeze-dried. Dried flesh was removed using forceps, and dried flesh and shell were weighed separately. Dried flesh for analyzing organic carbon, nitrogen, phosphorus, and caloric value was powdered and homogenized using an agate mortar and pestle.

Analytical methods. Organic carbon and nitrogen were determined using an elemental analyzer (Yanaco CHN corder MT5). Total phosphorus was determined colorimetrically with a Technicon Autoanalyzer using the molybdate blue method (Technicon Industrial Method No. 155-71W) after digestion using an autoclave (121°C for 3 h) in potassium persulfate (6.7 g l^{-1}) and sulfuric acid (0.25 N). The caloric value was determined using a bomb calorimeter (Shimadzu CA-4P), using about 10 g of powdered samples.

Mussel biomass. *Musculista senhousia* biomass in Lake Nakaumi was studied along 14 transects (Fig 2) in November 1996 and March 1997. Sediment (0.1 m^2) was collected using a Smith-McIntyre grab sampler

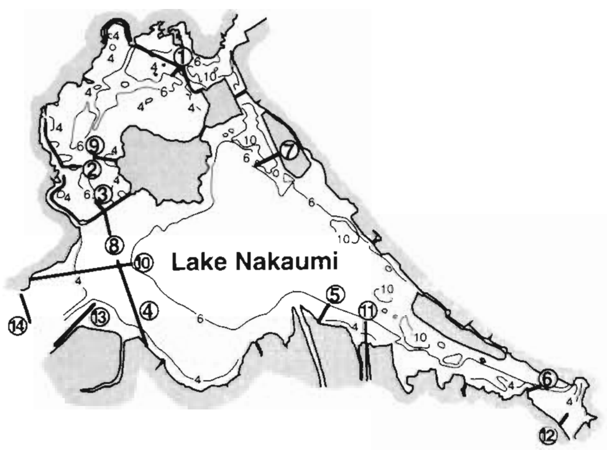

Fig. 2. Transects along which sediment sampling was conducted to count *Musculista senhousia* biomass in Lake Nakaumi. Water depth is in meters

every 1 m of depth along the transect and sieved in a nylon bag (mesh: 0.5 mm) on the boat. At each transect, the position of the boat was first determined with GPS, then moved slightly to the planned depth. Sampling was not done at the bottom where depth was irregular due to potential dredging problems. Macrobenthos was separated from the residue within a day in the laboratory. The wet weight of *M. senhousia* was determined after removing the byssal threads.

Table 1. *Aythya* spp. Comparison of gizzard weight (g; mean ± SE, number in parentheses) of wintering diving ducks for lakes and gender. Significant differences were analyzed by unpaired *t*-test

Lakes	Lake Nakaumi	Lake Shinji	p
A. fuligul	38.9 ± 4.7 (8)	70.2 ± 3.0 (20)	<0.0001
A. ferina	37.0 ± 1.9 (21)	77.9 ± 7.6 (3)	<0.0001
A. marila	30.9 ± 0.8 (5)	84.5 ± 4.2 (9)	<0.0001
Gender	Male	Female	p
A. fuligul	67.0 ± 5.0 (16)	53.7 ± 4.9 (12)	0.073
A. ferina	44.3 ± 4.7 (15)	38.4 ± 4.6 (9)	0.412
A. marila	58.6 ± 13.8 (6)	70.4 ± 8.8 (8)	0.463

RESULTS

Digestive organ content suggests that *Aythya* spp. collected from Lake Nakaumi and Lake Shinji chiefly consumed the bivalves dominant in each lake. More than 90% of *A. fuligula* caught in gill nets in Lake Nakaumi (n = 14) contained only *Musculista senhousia* in their digestive organs, while 80% of *A. fuligula* caught in Lake Shinji (n = 29) contained only *Corbicula japonica* (shells without flesh were not counted). Likewise, 62% of *A. ferina* caught in Lake Nakaumi (n = 21) contained only *M. senhousia*, while the 3 individuals caught in Lake Shinji contained only *C. japonica*. All *A. marila* caught in Lake Nakaumi (n = 5) contained *M. senhousia* and small amounts of a bivalve, *Tapes philippinarum*, and all individuals (n = 9) caught in Lake Shinji contained only *C. japonica*.

No significant difference in body weight was seen between lagoons or gender for all *Aythya* spp. ($p > 0.075$ by unpaired *t*-test). The gizzard weight of *Aythya* spp. caught in Lake Shinji was double that of species caught in Lake Nakaumi (Table 1), although the difference in gizzard weight between genders was negligible (Table 1).

Temporal changes in the amount of nitrogen and phosphorus per individual studied for *Aythya fuligula* (Fig. 3) increased from October to March, although they varied greatly, presumably because of the small number of specimens limited by the sample collection method.

Musculista senhousia tripled in flesh dry weight from October to March (Table 2). The relative density

Table 2. *Musculista senhousia*. Changes in weight and carbon, nitrogen, and phosphorus content of mussels collected at the east end of the Ohashi River from October 1994 to March 1995. Mean and SD of weight were calculated with 10 randomly selected individuals. About 200 individuals were powdered and homogenized for carbon, nitrogen, and phosphorus measurements determined 3 times

Month	Total wet weight per individual (mg)		Flesh dry weight per individual (mg)		Shell weight/Total wet weight (%)		Flesh carbon (wt%)		Flesh nitrogen (wt%)		Flesh phosphorus (mg g^{-1})	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
October	274	85	9.39	2.60	27.8	5.8	48.6	0.68	9.42	0.12	7.24	0.22
November	379	130	16.6	7.13	28.2	7.1	44.8	0.11	8.70	0.01	6.26	1.08
December	493	157	24.0	7.92	26.7	2.4	44.9	0.98	8.70	0.20	6.77	0.18
January	414	93	18.9	4.46	28.0	2.1	41.7	0.02	8.36	0.03	5.75	0.25
February	450	96	25.3	4.03	29.8	3.3	39.4	0.12	7.40	0.15	5.41	0.33
March	495	101	29.7	7.87	29.5	3.6	37.7	0.66	7.11	0.23	5.32	0.20

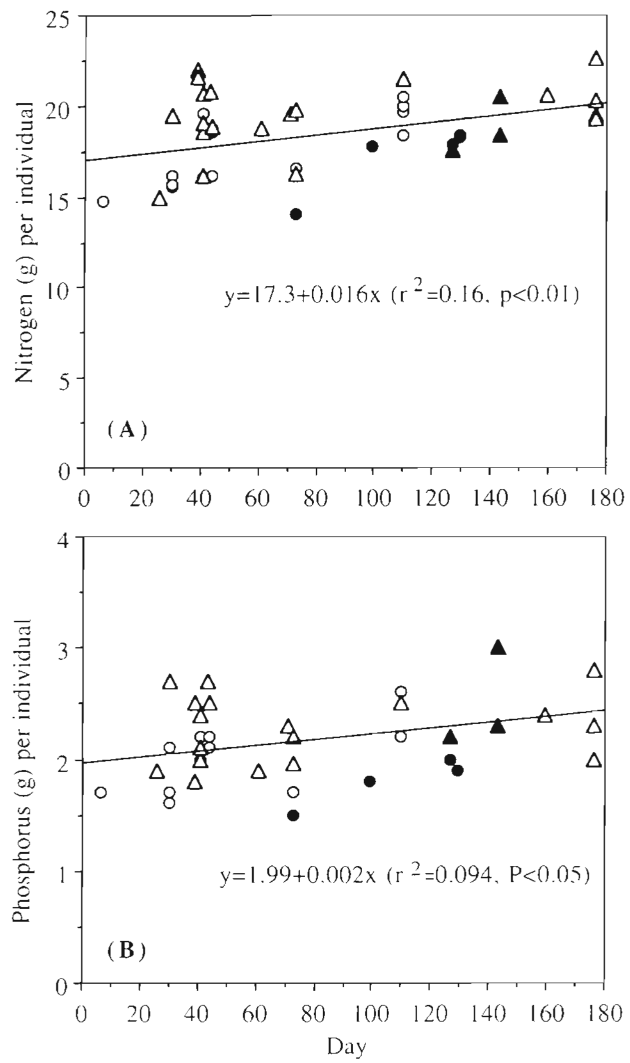

Fig. 3. *Aythya fuligula*. Changes in nitrogen and phosphorus per individual versus day caught by gill net during winter from October 1994 to March 1995. (●) Lake Nakaumi, female; (▲) Lake Nakaumi, male; (○) Lake Shinji, female; (△) Lake Shinji, male. October 1, 1994 was defined as Day 0. Regressions were calculated for all samples with the day (x) as an independent variable and nitrogen and/or phosphorus as a dependent variable (y)

of shell (in Table 2) increased simultaneously. Carbon, nitrogen, and phosphorus contents of dry flesh decreased slightly.

Caloric value of dry *Corbicula japonica* flesh was 18.0 kJ g^{-1} in October and November 1994 and 18.2 kJ g^{-1} in March 1995 (mean = 18.1 kJ g^{-1}). Corresponding values for *Musculista senhousia* were 17.3, 17.2, and 18.3 kJ g^{-1} (mean = 17.6 kJ g^{-1}).

Presence of *Musculista senhousia* was observed at 42 of 61 sampling points either in November 1996 or March 1997 (Fig. 4). The *M. senhousia* biomass decreased markedly at most sampling points during wintering by diving ducks. The average and minimum – maximum biomass (wet weight) of *M. senhousia* at the 42 sampling points was 1126 (0 to 5600) g m^{-2} in November 1996 and 24 (0 to 435) g m^{-2} in March 1997.

DISCUSSION

Diving ducks in Lake Nakaumi and Lake Shinji chiefly consumed filter-feeding bivalves taking up phytoplankton growing within lagoons. Nutrients in duck excrement would therefore not increase the total (dissolved and particulate) nitrogen and phosphorus in lagoon water. Instead, the amount of nutrients accumulated during their stay would be removed from the water when they leave the lagoons. If the accumulation of nitrogen in any individual *Aythya fuligula* during its 180 d stay from October to March is taken to be 2.9 g and that of phosphorus 0.36 g (Fig. 3), nitrogen and phosphorus accumulated by the average population of *A. fuligula* in both lagoons (26532 in Lake Nakaumi and 6845 in Lake Shinji for 1986 to 1995, Wild Bird Society of Japan, Shimane Prefecture Branch unpubl.) would be 97 kg for nitrogen and 12 kg for phosphorus. This amount, although small, is removed from lagoons when ducks migrate in spring.

The difference in the gizzard weight of *Aythya* spp. for Lake Nakaumi and Lake Shinji (Table 1) suggests

Table 3. Estimation on caloric requirement of *Aythya* spp. wintering in Lake Nakaumi. Mean weight and SD were calculated with samples from this study. Caloric requirement was calculated using conversion of 2.8SMR (standard metabolic rate) of active birds (Kooyman et al. 1982) and an assimilation efficiency of 73% (Cooper 1980). SMR was calculated from the allometric formula (Lasiewski & Dawson 1967): SMR (kJ d^{-1}) = $4.184 \times 78.3W^{0.723}$ where W is bird weight in kg. The mean population was calculated from data for 10 yr (1986 to 1995, Wild Bird Society of Japan, Shimane Prefecture Branch unpubl.)

	Weight of duck (kg)		Caloric requirement per individual (kJ d^{-1})	Lake Nakaumi population (no. of ind.)		Caloric requirement per population (MJ d^{-1})
	Mean	SD		Mean	SD	
Aythya fuligula	0.867	0.089	1133	26532	9416	30061
Aythya ferina	0.993	0.151	1250	18042	7577	22553
Aythya marila	1.145	0.079	1386	5702	2078	7903
Total						60517

that less effort is needed to digest *Musculista senhousia* (from Lake Nakaumi), which has a much thinner shell (shell weight/total wet weight = 27 to 30%, Table 2) than *Corbicula japonica* (shell weight/total wet weight = 83 to 85%, Nakamura et al. 1988), and that *Aythya* spp. do not often move between lagoons. The gizzard weight of *Aythya* spp. caught in Lake Nakaumi was half that of those caught in Lake Shinji, so we estimated the amount of *M. senhousia* grazed by diving ducks assuming that ducks in Lake Nakaumi ate exclusively *M. senhousia*.

Diving ducks in Lake Nakaumi require *Musculista senhousia* more to meet energy needs than for nitrogen and phosphorus requirements. The average population of *Aythya* spp. wintering in Lake Nakaumi would require 60517 MJ d^{-1} (Table 3). To meet this requirement by feeding on *M. senhousia*, whose caloric value was ca 17.6 kJ g^{-1} in flesh, ducks would have had to ingest 3438 kg of flesh d^{-1}.

Table 4 summarizes the estimated numbers of *Musculista senhousia* consumed by *Aythya* spp. in Lake Nakaumi assuming that the average wintering population consumes 3438 kg of *M. senhousia* flesh per day. Nitrogen and phosphorus in prey was also estimated based on the *M. senhousia* composition (Table 2). This suggests that the average wintering population of *Aythya* spp. consumes 3.5×10^{10} *M. senhousia* individuals during their stay. This predation by diving ducks most likely induced the extinction of *M. senhousia* in the lagoon (Fig. 4).

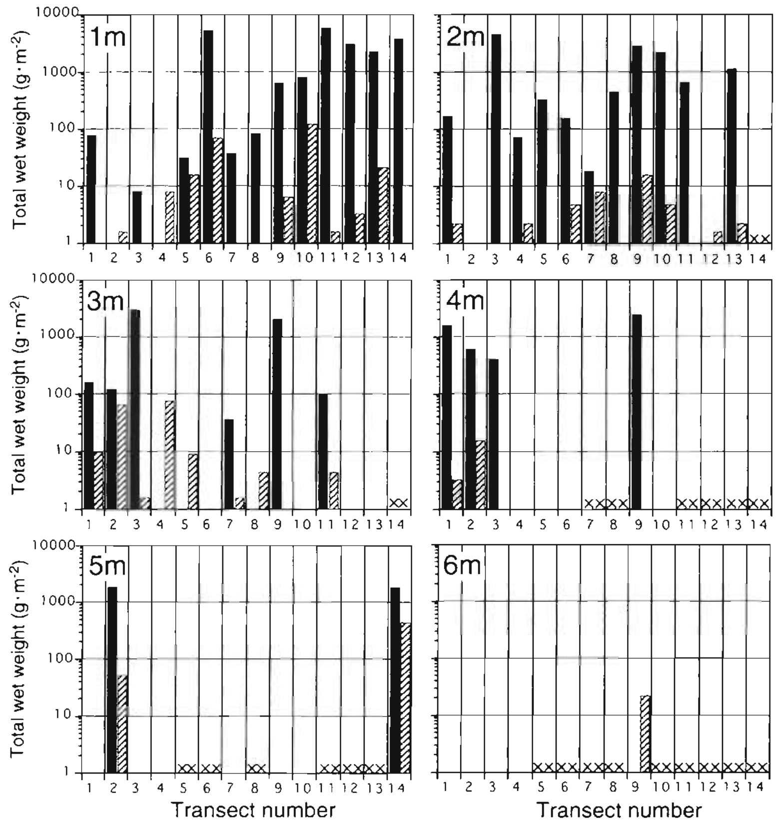

Fig. 4. *Musculista senhousia*. Biomass of mussels sampled in November 1996 (solid bars) and March 1997 (hatched bars) at different depths along the 14 transects in Fig. 2. The *y*-axis (biomass) is a log scale. Water depth is shown in meters. ×: sediment was not sampled at the depth along that transect

Table 4. Estimated number of *Musculista senhousia* eaten per month by 3 species of *Aythya* spp. wintering in Lake Nakaumi from October 1 to March 31, and the amount of carbon, nitrogen, and phosphorus contained in *M. senhousia* flesh

Month (no. of days)	Number of *M. senhousia*	Nitrogen (t) contained in *M. senhousia* flesh	Phosphorus (t) contained in *M. senhousia* flesh
October (31)	1.14×10^{10}	10.0	0.772
November (30)	6.21×10^{9}	8.97	0.646
December (31)	4.44×10^{9}	9.27	0.722
January (31)	5.64×10^{9}	8.91	0.613
February (28)	3.80×10^{9}	7.12	0.521
March (31)	3.59×10^{9}	7.58	0.567
Total	3.50×10^{10}	51.9	3.84

Most nitrogen (52 t) and phosphorus (3.8 t) in the flesh of *Musculista senhousia* would be excreted into Lake Nakaumi as feces and urine because the accumulation in ducks is small. Although excreted nutrients may stimulate the growth of phytoplankton, total nitrogen and phosphorus concentrations in Lake Nakaumi do not usually increase during the ducks' stay (Kato et al. 1996). Because water exchange with the sea is estimated to be 16 d (Kamiya 1988), excreted nutrients would not contribute to the growth of phytoplankton in warmer seasons. Feces accumulated at the bottom of the lagoon hardly induced bottom-water anoxia in winter (Metocean Co. 1994).

Without the diving ducks, the huge *Musculista senhousia* biomass would likely die in summer due to anoxia as often happens in Lake Nakaumi because water stratification develops easily at this time (Metocean Co. 1994). *M. senhousia* predators are generally absent in Lake Nakaumi in spring and summer because carnivorous invertebrates (i.e. crabs, shrimps, and gastropods) escape to the ocean during the cold season and only few return to water with a low oxygen concentration in warmer seasons. *M. senhousia* death by suffocation in summer would add a certain nitrogen and phosphorus load to the lagoon in the form of mussel flesh. Mussel flesh decomposition at the bottom in summer would also accelerate oxygen depletion, which would increase nutrient efflux from sediment.

In terms of calories, the biofouling mussel *Musculista senhousia* is a better food source for ducks than the commercial clam *Corbicula japonica* because their shells are much thinner. Mean flesh caloric values were nearly identical—17.6 kJ g^{-1} for *M. senhousia* and 18.1 kJ g^{-1} for *C. japonica*. *M. senhousia*, which lives above the sediment in high densities, would also be easier for ducks to collect than infaunal clams.

In Lake Nakaumi, biofouling mussel predation by diving ducks during winter thus may prevent water quality from deteriorating due to mussel death during summer, when nuisance phytoplankton blooms and anoxia occur easily.

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