# Extinction risk analyses in long-lived invertebrates

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**Key Words:** Biwa pearly mussell, pollution, overfishing, habitat loss, redlist

## Abstract

Many freshwater shellfishes are threatened, mainly caused by environmental degradation, habitat loss, overfishing and invasion of exotic species. Biwa pearly mussell *Hyriopsis schlegeli* (Martens, 1861), which is an endemic species of Lake Biwa, drastically decreased due to all these factors. The past catch statistics suggest that this mussel should be ranked as endangered, the mean time to extinction is shorter than 100 years. The growth rate significantly decreased with the past 40 years, which is not explained by overharvesting, habitat loss of dredging or invasion of exotic species into Lake Biwa.

## 1. Introduction

Many freshwater shellfishes are threatened, caused by environmental degradation, habitat loss, overfishing and invasion of exotic species. Biwa pearly mussel, *Hyriopsis schlegeli* (Martens, 1861), is an endemic subspecies of Lake Biwa and its satellite lakes, Shiga prefecture, Japan. This mussel is long-lived (Fig. 1) and has been exploited for pearl industry. The freshwater pearl industry in Japan has been threatened, mainly due to import of freshwater pearl from China.

We have very few data on population or stock size in shellfishes, even which are commercially exploited. Factors of threatenedness in shellfishes are not only overfishing, but also habitat loss, environmental degradation and invasion of exotic species. Even after collapse of commercial fishing, the population of Biwa pearly mussel has not been recovered. One of the most critical problems on this mussel is short of recruitment. Because of a long longevity and a high survival rate of adults, the population decline rates of these mussels are not significant. Therefore, we need to investigate effects of these factors on extinction risk of these shellfishes.

Lake Biwa is characterized by the biggest lake in Japan (672km$^2$), very long history (400 000 years) and many endemic fishes and shellfishes. Surrounding the lake, human

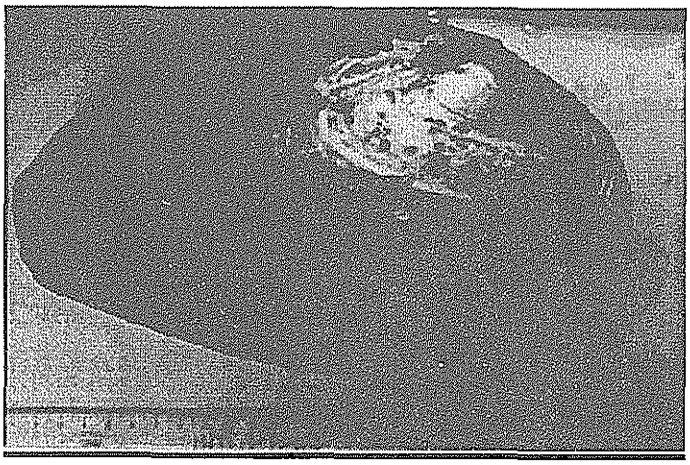

Fig. 1. Biwa pearly mussel (circa 40 years old, photo by K.Nishimori).

population is 1.3 million (Shiga Prefecture). Environmental conditions of Lake Biwa are threatened in (1) habitat loss of many endemic species, (2) eutrophication, (3) overfishing and (4) invasion of exotic species.

## 2. Fisheries extinction of Biwa pearly mussel

There were many pearl aquaculture fields in Lake Biwa. The catch of Biwa pearly mussel were over 10 metric tons during the early 1970s, drastically decreased in the 1980s and has been collapsed in 1992, as shown in Fig. 2. Extinction of commercial fisheries does not mean biological extinction. The Biwa pearly mussel still persists in lake Biwa. Despite of the fisheries extinction, we suspect that the population density and the area of occupancy of this mussell also decreased. From a mark-recapture survey, the current population size is circa 10000 (K. Nishimori, pers. comm.). Because the body weight per adult is about 30g, the annual catch in number in year *t*, denoted by $C(t)$, during 1970 to 1972 was circa 2 million.

Let logarithm of the ratio $\ln[C(t)/C(t-1)]$ be $r(t)$, which represents the annual rate of population increase if the catch in number is approximately proportional to the population size.

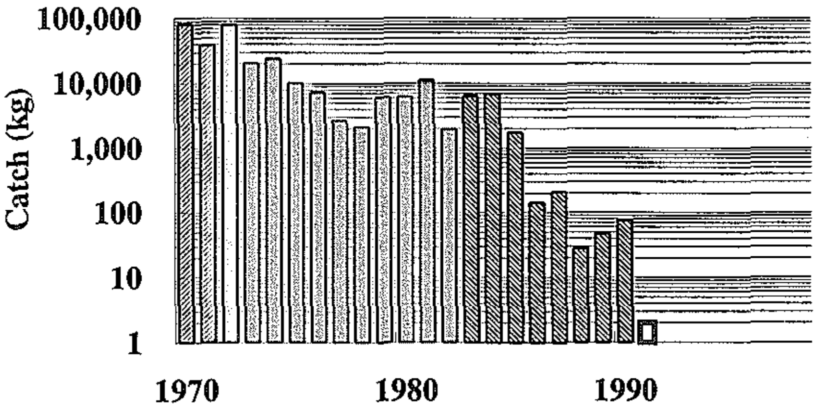

Fig. 2. Catch of Biwa pearly mussell in Lake Biwa during 1970 to 1997 (source: Project Report of Shiga Prefectural Fisheries Experimental Station). Periods I-IV are distinguished by different hatching patterns.

H. Kawai (unpublished) divided history of Biwa pearly mussel fishery into four periods; (I) 1954-1973, (II) 1974-1982 and (III) 1983-1990 and (IV) 1991-1998. Each period is characterized by (I) fisheries development, (II) overfishing, (III) collapse and (IV) fisheries extinction. In 1991, the recorded catch was 2kg. Since 1992, this mussel has never been landed into fisheries market, despite of presense of bycatch.

In almost every year, $r(t)$ was negative. The average(±standard deviation) during period II and III are respectively -0.126±0.848 and -0.701±1.142. The latter is much larger than the former, probably because fishing effort during period III decreased from year to year. Since there is no significant factor to decrease fishing effort during period II, I assume that the fishing effort during period II was kept constant and the catch in number during period II is proportional to the population size, denoted by $N(t)$.

If $r(t)$ and the current population size $N_0$ is given, the extinction probability within the next t years, denoted by $g(t)$, is given as

$$g(t) = \int_0^t p(\tau)d\tau\,, \qquad \text{(1a)}$$

where the probability density $p(t)$ is given as

$$p(t) = \frac{(x_0 - x_c)}{\sqrt{2\pi\sigma^2 t^3}} \exp\left[-\frac{(x_0 + r^* t - x_c)^2}{2\sigma^2 t}\right], \quad \sigma^2 = \sigma_r^{\,2}\left[1 + 2\sum_{\tau=1}^{\infty} \rho(\tau)\right], \qquad \text{(1b, c)}$$

$x_0 = \log N_0$, $x_c = 1$, $r^*$ is the mean of $r(t)$, $\sigma_r^2$ is the variance of $r(t)$, $\rho(\tau)$ is the autocorrelation of $r(t)$ with time lag $\tau$. We ignored autocorrelation and assumed $\sigma = \sigma_r$. Extinction is driven by (1) deterministic decline, (2) environmental stochasticity and (3) demographic stochasticity. The above formula includes deterministic decline and environmental stochasticity, but ignores demographic stochasticity. This gives an underestimation of extinction probability.

The mean time to extinction, denoted by $T$, is given as

$$T = \int_0^\infty [1 - g(t)]dt\,. \qquad \text{(2)}$$

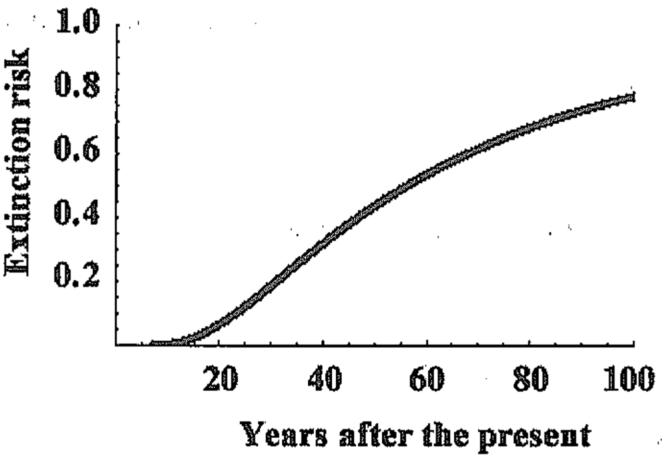

Fig. 3. Extinction risk $g(t)$ of the Biwa pearly mussel within the next $t$ years.

In period II, the mean population decline rate is 12% per year. Despite of large uncertainty and interim assumptions, this formula would give an indicator of extinction risk. If the average and SD of the decline rate during this period will continue in the future, I can obtain the extinction risk from Eq.(1), as shown in Fig. 3.

The generation time of the Biwa pearly mussel is about 12 years (Kondo pers.comm.). In accordance with the redlist criteria given by the World Conservation Union (IUCN) in 1994, a taxon is ranked as endangered if the extinction probability within the next 5 generations or 20 years, whichever is longer, is larger than 20%. In the case of the Biwa pearly mussel, the extinction probability within the next 60 years or 5 generations is above 20%, or 44%, which should rank as endangered by criterion E (IUCN 1994). The mean time to extinction $T$ is estimated to be 73 years. This subspecies should be listed as Endangered, despite the fact that this mussel was not listed at any rank of threat in the Red Data Book of Japan (Environment Agency of Japan 1991),

Because of fisheries extinction in 1992, the population decline rate since period IV may be smaller than the rate during period II. However, this mussel decreased not only by overfishing but also by habitat loss, invasion of exotic fish species and environmental degradation. If the population size in 1997 is 10000 and the mean annual decline rate is 12%, the population size in

1982 is 55000. However, catch in number in 1982 was 60000, which was larger than the population size. It suggests that the population decline rate in period III should be larger than 12%, mainly due to overfishing.

## 3. Decrease of growth rate in Biwa pearly mussel

The past growth rate of Biwa pearly mussel, observed in 1957, was much higher than the rate, observed in 1997 (Nishimori 1998). Nishimori (1998) measured all annual ring radii of each sample individual. The shell size at age $a$ of over 10 year-old individuals is significantly larger than the shell size at the same age $a$ of under 7 year-old individuals, as shown in Fig. 4. The age of maturity depends on the shell size. The shell size is a better indicator of maturity than the age. The size of maturity is circa 70mm. Decrease of growth rate makes a long generation time.

Invasion of exotic species may threat native species for several reasons. Exotic species may either compete or exploit native species. In addition, exotic species may starve native species of its prey or host. There are many indirect effects of species invasion throughout the community. In the 1960s, bluegill *Lepomis macrochirus* was introduced into Japan. The bluegill has once been expected to be a suitable host of the glochidium larvae of the Biwa pearly mussel, but it threatened many native host fishes of the Biwa pearly mussel in the 1980s (Nakai 1999).

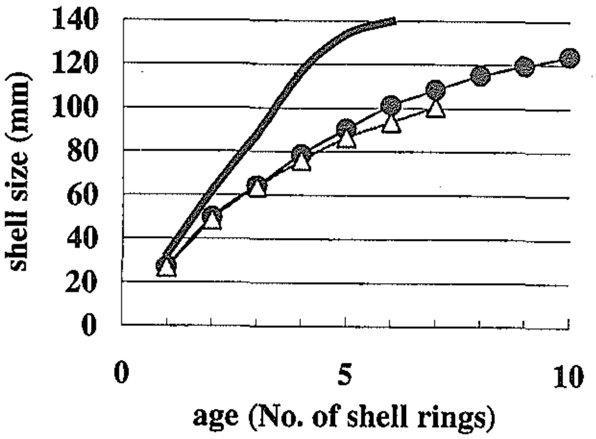

Fig. 4. Decrease of growth rate of the Biwa pearly mussel. Past data (1957, bold curve) is much faster than present data (over 10 year-old individuals, filled circles; under 7 year-old individuals, open triangles).

We have very few experimental data of these risk factors on biological extinction. To compare risk factors of biological extinction between overfishing, habitat loss, water pollution and invasion of exotic species, we consider an imaginary population, which has a simple size-structure dynamics:

$$\mathbf{G}_\Delta = \begin{pmatrix} (1-g_1)p_1 & 0 & \cdots & 0 & 0 \\ g_1p_1 & (1-g_2)p_2 & \ddots & 0 & 0 \\ 0 & g_2p_2 & \ddots & \vdots & \vdots \\ \vdots & 0 & \ddots & (1-g_{c-1})p_{c-1} & 0 \\ 0 & \cdots & \ddots & g_{c-1}p_{c-1} & p_c \end{pmatrix}, \qquad (3)$$

where $\mathbf{n}_t=(n_{1,t}, n_{2,t},\ldots, n_{c,t})^{\mathrm{T}}$ is a column vector indicating size structure of the population at time $t$; each element $n_{i,t}$ is the number of individuals in size class $i$ at time $t$; $\mathbf{G}_\Delta$ is the transient matrix, indicating size-dependent growth rate $g_i$ and survival rate $p_i$.

Since I consider a very short time interval $\Delta t$ (measured by year); the probability that an individual in class $i$ at time $t$ becomes size class $i$+2 at time $t+\Delta t$ is negligible. If I ignore seasonal variation in transient matrix $\mathbf{G}_\Delta$, I obtain the transient matrix that represents yearly change of size structure:

$$\mathbf{G} = (\mathbf{G}_\Delta)^{(1/\Delta t)}. \tag{4}$$

If the reproduction season comes once a year, the reproduction matrix is

$$\mathbf{E} = \begin{pmatrix} 0 & \cdots & m_i s & \cdots & m_c s \\ 0 & \cdots & 0 & \cdots & 0 \\ 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \ldots & 0 & \cdots & 0 \end{pmatrix}, \tag{5}$$

Let **e** be the first row vector of **E**; **e**=(0,..., $m_i s$, $m_{i+1} s$,..., $m_c s$). The full transition matrix of the size-structured population is given as

$$\mathbf{n}_{t+\Delta t} = (\mathbf{G}_\Delta + \mathbf{E}_\Delta)\ \mathbf{n}_t, \tag{6}$$

The stationary size structure is given as the right eigenvaector (**n***) of **L**+**E** with respect to the maximum eigenvalue ($\lambda$): $(\mathbf{L}+\mathbf{E}).\mathbf{n}^*=\lambda.\mathbf{n}^*$. The reproductive value is given as the left eigenvector (**r***) of **L**+**E** with respect to the maximum eigenvalue ($\lambda$): $\mathbf{r}^*.(\mathbf{L}+\mathbf{E})=\lambda.\mathbf{r}^*$. The reproductive value is proportional to

$$\mathbf{r} = \sum_{x\geq 1} \mathbf{e}.\mathbf{G}^{x-1}/\lambda^x = \mathbf{e}.(\mathbf{I}-\mathbf{G}/\lambda)^{-1}/\lambda, \tag{7}$$

where the first element of **r** (the reproductive value at birth)=1.

The generation time, denoted by $T_g$, is given as

$$T_g = \sum_{x\geq 1} x\mathbf{e}.\mathbf{G}^{x-1}/\lambda^x = \mathbf{e}.\left[(\mathbf{I}-\mathbf{G}/\lambda)^{-1}\right]^2/\lambda. \tag{8}$$

The maximum size class and the size of maturity are: $i_c$=20, $i_m$=11. I choose size-dependence in parameter values: $m_i=si^3$, $g_i=g_0(i_c-i)/i_c$, $p_i=p$ and parameters; $\Delta t$=1, $(g_0, p, s)$ = (0.05, 0.83015, 0.001) as a base case. In this case, the maximum eigenvalue and the average generation time are 1 and 21.40, respectively. I consider other 3 cases: (1) $g_0$=0.031, (2) $p$=0.78665 and (3) $s$=0.0000308. In any case of these, the maximum eigenvalue becomes 0.95. The average generation time $T_g$ is 30.49 for case (1), 21.27 for case (2) and 24.87 for case (3).

The initial size structure is chosen as an eigenvector concerned with the maximum eigenvalue of the base case **L**. Population biomass is defined as $B_t=\sum m_i n_{it}$. Fig. 5(a) shows changes of the biomass within the next 100 years. Fig. 5(b) shows size structure at $t$=20.

In case (3), population decline is not significant in the first 2 decades. Since the survival rate of mature individuals did not decrease, the population biomass of mature individuals did not decrease in case (3). The frequency of mature individuals in case (3) is larger than that in the other cases.

A typical example of case (2) is overharvesting. The survival rate is less affected by environmental degradation, rather than the recruitment rate or the growth rate. In contrast, overharvesting decreases the survival rate. Environmental degradation, including water pollution, decreases the growth rate, which corresponds with case (1). Starvation of either larval host by invasion of exotic species or juvenile habitat by dredging decreases the recruitment rate, which corresponds with case (3). Endocrine disrupters decrease the reproduction rate, which also correspond with case (3). Fig. 5 might suggest that case (3) is less crucial than other cases.

However, overharvesting is often reversible. If overfishing is ceased, the population will soon recover. In contrast, emission of environmental chemicals affect recruitment and growth rate after source of these emission ceases. Impacts of environmental chemicals on biodiversity will affect over generations. Artificially organic chemicals are not easily decomposed over

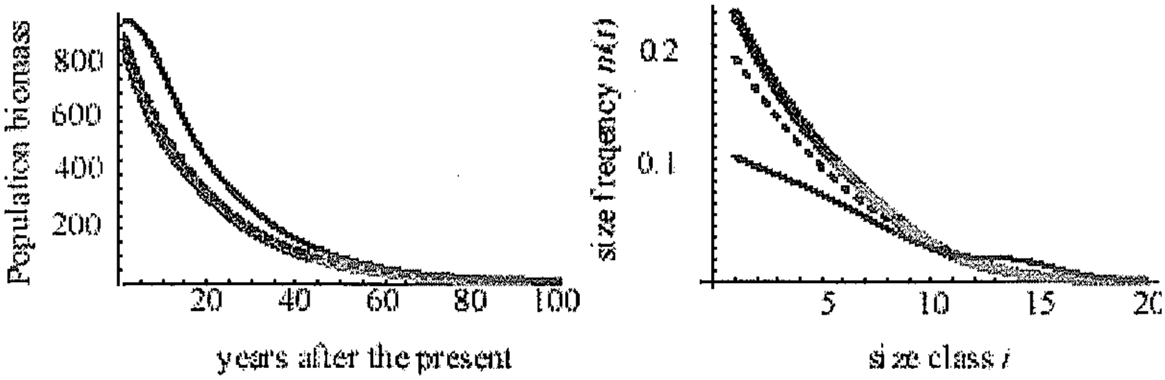

Fig. 5. Population declines of a size-structured population for cases (1), (2) and (3),

century. In addition, environmental chemicals affect a large number of species, not only economically valuable bioresources but also species that are not commercially utilized.

If some environmental chemicals decrease reproduction rate and growth rate, the populations decline from an early stage of pollution, get worse in the next generation and rarely cease.

The Biwa pearly mussel decreased by overfishing in the 1970s. Its habitat was almost lost by thorough dredging in south basin of Lake Biwa. Hosts of the glochidium larvae are several native fishes, e.g., trident goby *Tridentiger kuroiwae*.. These native fishes are threatened by invasion and increase of bluegill. Any of these factors does not cause the actual decrease of growth rate (Fig. 4). There must be another factor that decreases the growth rate, it may be environmental degradation.

The generation time varies with life-history parameters. Delay of growth rate and decrease of recruitment increases the average generation time. Increase of mortality by harvesting decreases ecological longevity and the intrinsic rate population increase; the former decreases the generation time and the latter increases it, and totally the generation time may either increase or decrease.

At final stage of population extinction, demographic stochasticity plays an important role when the extinction occurrs.

## 4. Acknowledgments

I thank H.Kawai, K. Nakai and K.Nishimori for valuable comments.

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