Ecological Risk Analysis in Japanese Lake : A Case Study Using the CASM

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Abstract

This paper presents a method for evaluating the potential risk posed by chemicals to aquatic ecosystems in Japan and applications of this method. The Comprehensive Aquatic Simulation Model is used to simulate population dynamics, including predator-prey interactions, under time-varying environmental conditions from the results of laboratory toxicity tests. The risks posed by chemicals are calculated as probabilities of the decrease in biomass using Monte Carlo simulations. The simulated biomass under no toxic stress was compared with the field observed biomass for species in Lake Biwa and relatively good agreement was observed between the two. One of the important results obtained using this method was that certain chemicals might decrease the biomass of insensitive species when their prey populations decrease in biomass, or their predator populations increase as a result of the effects of the chemicals.

1. Introduction

Combinations of experimental results and models often yield useful methodologies in various fields of our society. The 10^{-5} carcinogen risk of chemical substances, which is widely used for quality management of air, water, and soil, is a good example of the combination. To calculate the 10^{-5} carcinogen risk, the results of toxicity tests and a biologically based or case-specific model is used. If a bioassay analyst attempts to determine the concentration of chemicals which corresponds to a 10^{-5} carcinogen risk only through experiment, more than 1.6×10^{6} experimental animals will be required to detect such a low level of risk, since carcinogenicity tests are normally performed for at least three dose levels with controls for both

sexes of two species of animals. Using such a large number of animals for only one chemical substance is far from realistic in terms of environmental conservation.

It is also almost impossible to conduct an experiment to specify the toxicity of a chemical to wildlife that retain predator-prey relationships and the struggle for existence between species under natural time-varying conditions because of the difficulty of artificially maintaining such natural conditions. It is well known that the number of wildlife decreases if the populations of prey are reduced or those of predator are increased for some reasons. And some chemicals might become one of the reasons. Namely, a species that is insensitive to a chemical substance will decrease in number if its prey is sensitive to that chemical.

The purpose of this study is to develop a method for evaluating the potential risk posed by chemicals to aquatic ecosystems in Japan, using a model called the Comprehensive Aquatic Simulation Model (CASM; DeAngelis et al, 1989), which models an aquatic ecosystem to simulate population dynamics under the stress of the presence of toxic chemicals. Furthermore, one of the most important subjects in this study is to stockpile examples of the assessment, using this method, of toxic chemical substances, especially those already regulated because of their toxicological effects. This will assist decision making by providing a scale for comparing the actions we have already taken and those we should take next in the safety management of toxic chemicals.

2. Model

2.1 *Model structure*

The CASM simulates the daily production dynamics of populations inhabiting a water column, a littoral zone or a benthic zone (Fig. 1). The epilimnion supports one bacteria population, 10 functionally defined populations of phytoplankton, 5 zooplankton populations, 3 populations of planktivorous fish, and a single piscivorous fish population. The hypolimnion includes one bacteria population, 2 populations of benthic insects, 3 populations of larger

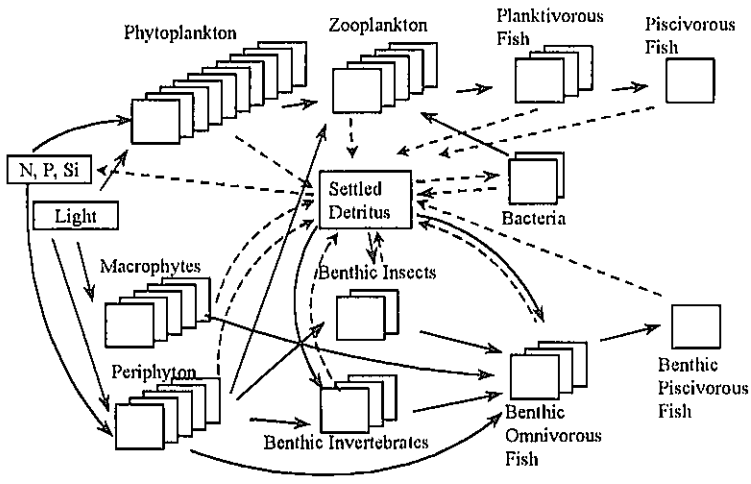

Fig. 1 Structure of the Comprehensive Aquatic Simulation Model

benthic invertebrates (e.g., clams and crayfish), 3 populations of omnivorous fish, and a single piscivorous fish population. The littoral subsystem includes 5 functionally defined populations of macrophytes and 5 periphyton populations.

The CASM also describes the dynamics of dissolved organic matter, particulate organic matter, settled detritus, and concentrations of nitrogen, phosphorus, silica, and dissolved oxygen. The hypolimnion receives organic-matter input in the form of detritus and sinking phytoplankton.

In this study, species inhabiting Lake Biwa, which is one of the representative aquatic environments in Japan, are considered (Table 1).

2.2 *Governing equations*

1) *Primary producer populations without toxic stress*

The change in biomass B [g-C/m^2] of the primary producers vs time t [d] is equated to

$$dB/dt = B\{P_m \cdot f(N, P, Si) \cdot g(I) \cdot h(T) - R \cdot h(T) - S - M - G\}, \quad (1)$$

where P_m is the photosynthesis rate constant [d^{-1}], M is the mortality rate constant [d^{-1}], and N, P, and Si are the concentrations of nitrogen, phosphorus, and silica [μg/L], respectively. I is the daily light intensity [E/m^2·h], T the water temperature [℃], R the respiration rate constant [d^{-1}], S the sinking rate constant [d^{-1}] (for phytoplankton only), and G a nonlinear function representing loss due to zooplankton grazing. This function is the same as the predation term described in the consumers section.

The first term on the right side of equation (1) represents the contribution of photosynthesis. The functions for nutrients f(N, P, Si), light intensity g(I), and temperature h(T) are

$$f(N, P, Si) = \min\{N/(k_N + N), P/(k_P + P), Si/(k_{Si} + Si)\} \quad (2)$$

$$g(I) = \frac{0.316[\exp\{(-I/I_S)\exp(-0.2z - 0.1Z)\} - \exp(-I/I_S)]}{0.2 + 0.1Z} \quad (3)$$

$$h(T) = \{(T_O + 10 - T)/10\}^{1.5}\exp[1.5 - \{1.5(T_O + 10 - T)/10\}], \quad (4)$$

where k_N, k_P, and k_{Si} are half-saturation constants for nitrogen, phosphorus, and silica [μg/L], respectively. I_S is the light saturation intensity [E/m^2·h], Z the sum of biomass values of all phytoplankton and periphyton populations [g-C;m^2], z the depth of the water column, and T_O the optimal temperature for growth, grazing, or respiration [℃]. Use of nutrients is determined by the Michaelis-Menten function. Light availability is modified by depth and by shading by the plant biomass. The temperature dependence of photosynthesis and respiration is determined by the Q_{10}-like function. The model populations respond differentially to daily changes in nutrient availability, surface light intensity, and water temperature, according to the values of

constants specified in the above equations. This represents that populations in the same trophic level compete against each other to obtain light and nutrients.

2) *Consumer Populations without toxic stress*

Growth rates of the consumer populations were determined using

$$\frac{dB_i}{dt} = B_i\{C(1-D-U)\cdot h(T) - R\cdot h(T) - M - G\}, \qquad (5)$$

where B_i is the biomass of the target population [g-C/m^2], C the consumption term, D the dynamic action constant [1/d], and U the egestion rate constant [1/d]. Loss to predation (G) was not applied to the piscivorous populations, which are the top carnivores in the food web.

The consumption term (C) and loss to predation (G) are

$$C = C_m \sum_j \{a_{ij} w_{ij} B_j / (B_i + \sum_j w_{ij} B_j)\} \qquad (6)$$

$$G = \sum_k \{C_{m_k} h(T_k) w_{ki} B_k / (B_i + \sum_k w_{ki} B_k)\}, \qquad (7)$$

where B_j is the biomass of prey for the target population [g-C/m^2], B_k the biomass of predator for the target population [g-C/m^2], C_m the maximum consumption rate constant [1/d], a_{ij} the assimilation of prey j by population i [−], w_{ij} the preference of predator i for prey j [−].

When prey are abundant, C is determined by the biomass of the predator. Conversely, the prey biomass determines values of C when prey biomass values are low or predators are abundant. Consumer populations are differentiated by their population-specific values of C_m, D, U, R, M, T_O, a_{ij}, and w_{ij}.

3) *Modeling toxic effects*

Changes in physiological processes such as photosynthesis, grazing, non-predatory death, and respiration, due to exposure to toxic chemicals are calculated by modifying equations (1) ～ (7) and simulating bioassay results reported for the chemicals of concern. Toxic effects were represented as population-specific effects factors, E[−]. Namely, P_m/E, I_s/E, $k_N \cdot E$, $k_P \cdot E$, $k_{Si} \cdot E$, $R \cdot E$, $S \cdot E$, and $M \cdot E$ are used instead of P_m, I_s, k_N, k_P, k_{Si}, R, S, and M, respectively, for primary producer populations in equations (1) ～ (4). Similarly, C_m/E, $D \cdot E$, $U \cdot E$, $R \cdot E$, and $M \cdot E$ are used instead of C_m, D, U, R, and M, respectively, for consumer populations in equations (5) ～ (7). Furthermore, E was determined for each combination of a chemical and a population by simulating a toxicity test that had been reported in the examination of IC_{50}, EC_{50}, or LC_{50}.

The uncertainties in extrapolating laboratory data, via the bioassay simulations, to estimates of risk were incorporated by assigning the E values to statistical distributions. Each E value

was regarded as the mean of a normal distribution with a standard deviation equal to the mean, i.e., a coefficient of variation of 100%. The Monte Carlo method was used to express the risks posed by chemicals as probabilities of decrease in biomass.

3. Results and Discussions

3.1 *Seasonal changes of biomass without toxic stress*

Fig.2 shows the comparison of the seasonal change of the biomass observed in Lake Biwa and of the simulated biomass for 10 populations of phytoplankton without toxic stress. Although the simulation can't follow the entire natural change of the biomass, relatively good agreement was observed between the two.

3.2 Examples of the results of the risk calculation

Fig. 3 shows examples of the estimated risks for three chemical substances. Toxicity values for the model population were assigned as follows. First, major species inhabiting Lake Biwa were listed. Lake Biwa was selected because it is one of the representative aquatic environments in Japan. Next, toxicity values for those species were collected from reports, papers, and documents published by government and/or scientific societies in Europe, America, and Japan. If there were no data available for a certain species, toxicity values surveyed for the same genus were applied. If these also were unavailable, toxicity values for organisms belonging to the same trophic level and behaving similarly were used. Geometric means were taken when more than one value was obtained for one species from different sources.

Environmental concentrations of chemicals were assumed to be half the lowest toxicity value for each compound listed in Table 1. In the case of DDT, zooplankton and piscivorous fish populations are more sensitive than other populations. As a result, there are direct effects on both zooplankton and piscivorous fish. Furthermore, planktivorous fish, which is relatively insensitive to DDT, is also decreased because of reductions in their food supply. On the other hand, phytoplankton increased in biomass because their predators were sensitive to the toxicant.

Four trophic levels of fish are relatively sensitive to pentachlorophenol (PCP). Therefore, those populations were directly affected and decreased in biomass. Because they occupy the top of the food web in an aquatic ecosystem, the other populations, except periphyton populations, tended to increase in biomass. The periphyton biomass affected the increase of benthic insects and benthic invertebrates, i.e., their predators.

For naphthalene, phytoplankton increased in biomass in spite of the relatively low toxicity values. This is why the endpoint of the toxicity tests is growth inhibition for primary producers instead of lethality for consumers, and phytoplankton populations responded to the decrease of their predator or zooplankton populations. On the other hand, periphyton populations responded to both direct toxic effects and increase of benthic insect populations. Planktivorous fish and piscivorous fish populations responded to both direct toxic effects and reductions in their food supply.

4. Acknowledgment

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5. References

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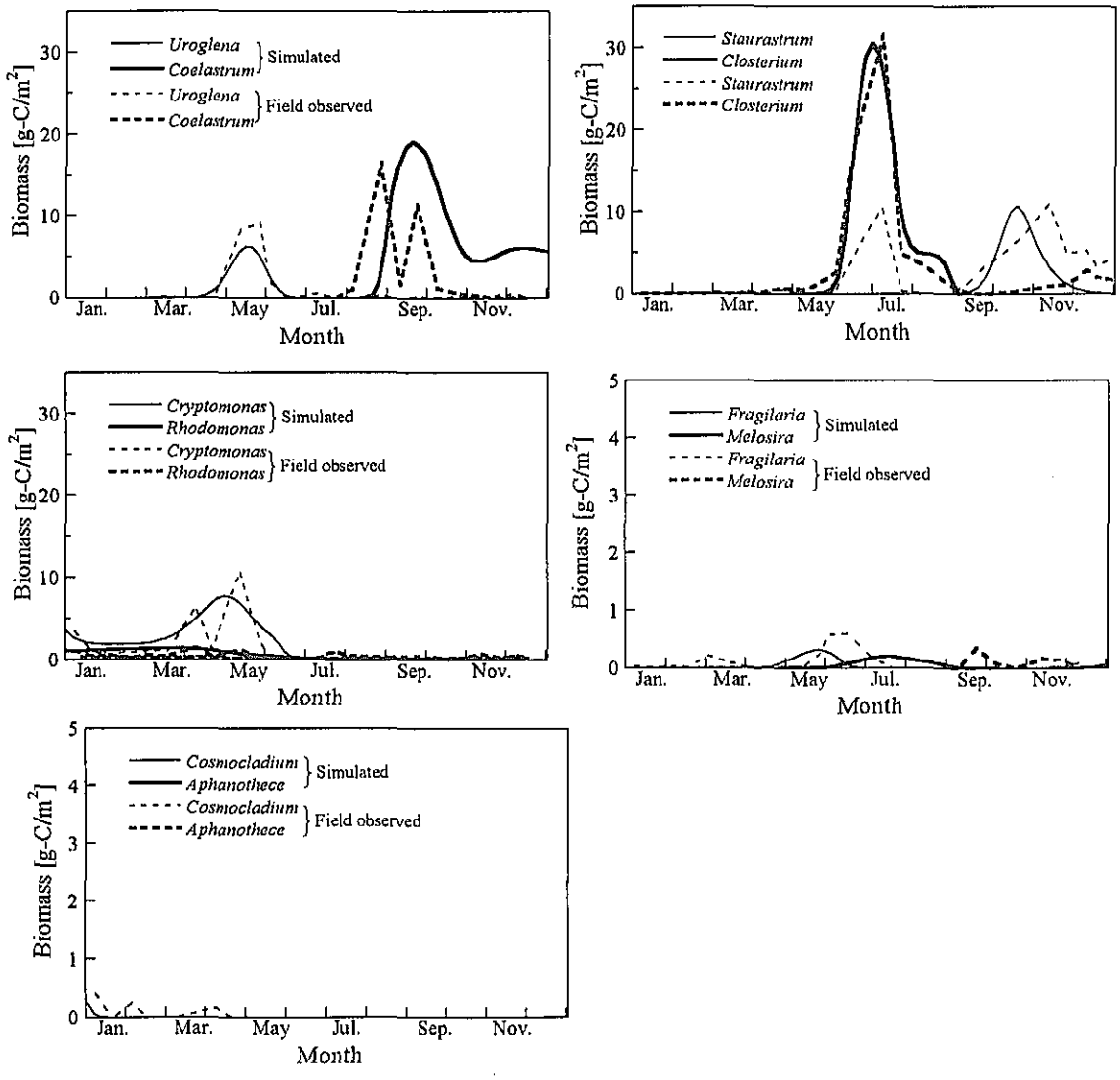
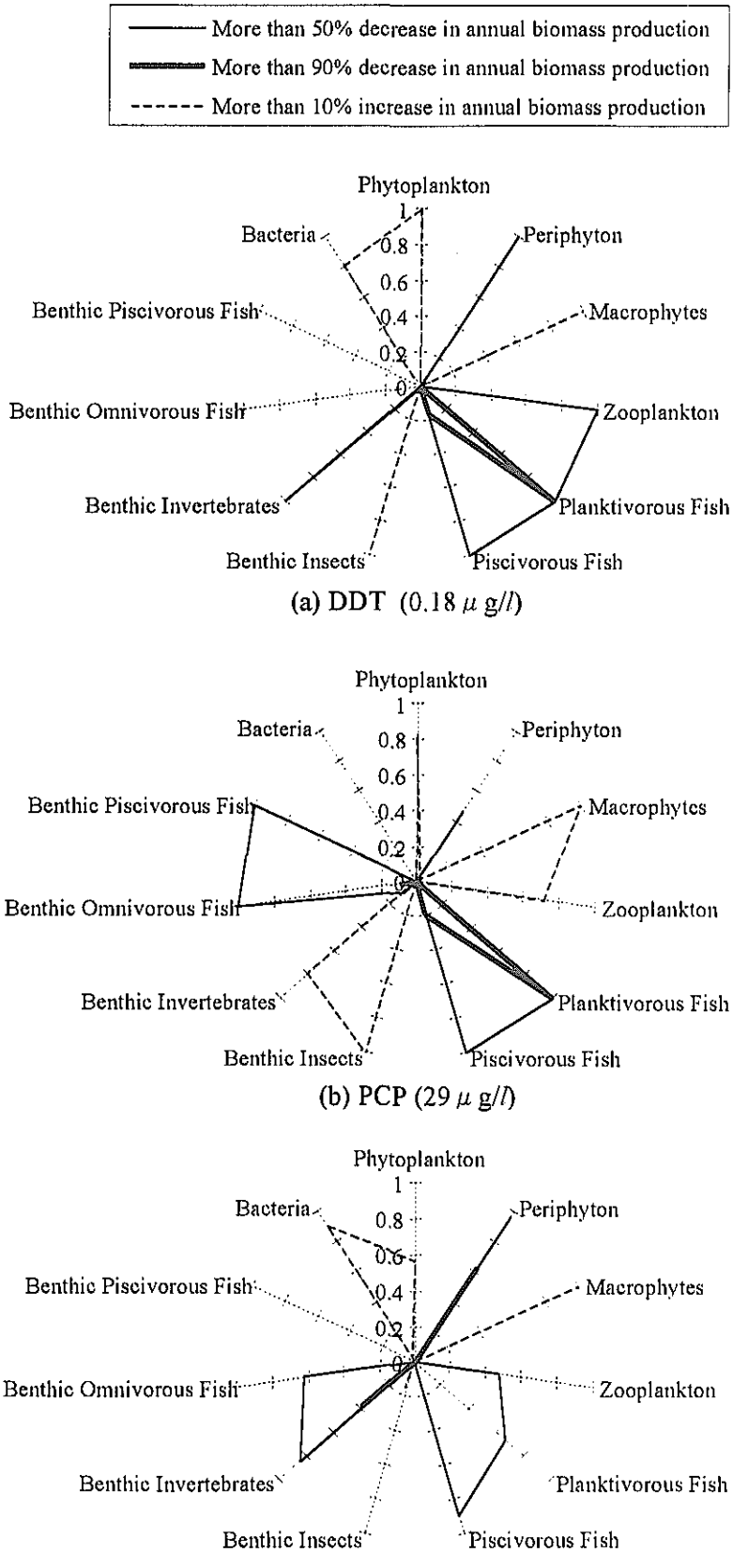


Fig. 2 Seasonal changes of the biomass observed in Lake Biwa and of the simulated biomass

The biomass of populations inhabiting Lake Biwa was observed in 1992. Environmental conditions used for above simulation such as water temperature and nutrients concentration were measured in Lake Biwa in the same year.



(a) DDT (0.18 μ g/*l*)

(b) PCP (29 μ g/*l*)

(c) Naphthalene (0.12mg/*l*)

Fig. 3 Risk of specific ecosystem effects for three chemical substances

Table 1 Species inhabiting in Lake Biwa and toxicological data used to estimate risk (IC_{50} for primary producers, EC_{50} for Zooplankton, and LC_{50} for the other consumers)

Phytoplankton	DDT [μg/l]	PCP [μg/l]	Naphthalene [mg/l]
1 *Uroglena americana*	253 *#	184 ***	0.417 **#
2 *Fragilaria crotonensis*	214 *#	184 ***	0.233 **#
3 *Melosira granulata*	238 *#	184 ***	0.233 **#
4 *Cryptomonas sp.*	253 *#	184 ***	0.417 **#
5 *Rhodomonas sp.*	253 *#	184 ***	0.417 **#
6 *Staurastrum dorsidentiferum var. ornatu*	198 *#	222 ***	0.250 **#
7 *Coelastrum cambricum*	198 *#	80 ***	0.250 **#
8 *Closterium aciculare var. subpronum*	198 *#	187 ***	0.250 **#
9 *Cosmocladium constrictum*	198 *#	80 ***	0.250 **#
10 *Aphanothece clathrata*	253 *#	80 ***	0.417 **#
Periphyton			
1 *Gomphonema scuminatum*	238 *#	184 ***	0.233 **#
2 *Achnanthes lanceolata*	238 *#	184 ***	0.233 **#
3 *Cymbella turgida*	214 *#	184 ***	0.233 **#
4 *Navicula cryptocephala*	214 *#	184 ***	0.233 **#
5 *Nitzschis linearis*	253 *#	184 ***	0.233 **#
Macrophytes			
1 *Phragmites communis*	50000 ****	5500 *	33 **
2 *Zizania latifolea*	50000 ****	5500 *	33 **
3 *Trapa japonica*	50000 ****	5500 *	33 **
4 *Potamogeton malaianus*	50000 ****	5500 *	33 **
5 *Potamogeton perfoliatus*	50000 ****	5500 *	33 **
Zooplankton			
1 *Polyarthra trigla*	2.65 **	920 *	1.0 ***
2 *Synchaeta stylata*	2.65 **	2160 *	1.0 ***
3 *Bosmina longirostris*	0.36 **	670 ***	6.6 ***
4 Nauplius	1.20 **	475 ***	6.6 ***
5 *Eodiaptomus japonicus*	0.36 **	240 **	6.6 ***
Planktivorous fish			
1 *Hypomesus olidus*	30.3 ***	204 ***	5.31 ***
2 *Gnathopogon caerulescens*	67 ***	65 ***	2.4 ***
3 *Lepomis macrochirus*	5.31 ***	154 ***	150 ***
Game Fish			
1 *Micropterus salmoides*	1.20 ***	207 ***	1.92 ***
Benthic insects			
1 *Ichtinogomphus clavatus*	1.00 **	1750 ***	6.7 *
2 *Chronomidae*	4.70 *	1950 *	2.80 **
Benthic invertbrates			
1 *Macrobrachium longipes*	4.20 **	882 ***	2.60 *
2 *Cristaria plicata*	0.62 ***	1100 ***	3.90 **
3 *Semisulcospira bensoni*	25.8 ***	306 ***	5.00 **
Benthic omunivorous fish			
1 *Cyprinus carpio*	7.69 ***	85 ***	7.9 ***
2 *Carassius carassius*	43.4 ***	135 ***	2.59 ***
3 *Rhynogobius brunneus*	0.90 ***	442 ***	1.46 ***
Benthic game fish			
1 *Prasilurus asotus*	17.5 ***	58 ***	1.92 ***
Bacteria			
Epilimnion	1.29 **	80 ***	1.0 ***
Hypolimnion	1.29 **	80 ***	1.0 ***

Duration of the toxicity tests : * 24h, ** 48h, *** 96h, **** 7d

extrapolated data