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Study on a Water Environmental Problem From a Viewpoint of a Nonlinear Complex System

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Abstract–Toxic cyanobacteria grows in many eutrophicated lakes and causes many acute environmental problems. We analyzed the phenomena of vast proliferation of toxic cyanobacteria in an eutrophicated lake using a nonlinear model equation of population dynamics determined. In the nonlinear model equation of cyanobacterial we used, we focused on the interaction of rise of the pH and pressure from the zooplankton. The rise of pH is according to the proliferation of cyanobacteria. This equation was numerically solved and the vast proliferation of cyanobacteria was determined as a bifurcation phenomenon. However, it is not sufficient to only use simple and conceptual model analysises to tackle real environmental problems. To deal with the real complex system of natural environments or natural ecosystems, we are developing on a Lab-on-a-Chip device to rapidly measure the properties of many species of plankton and microbes in real water ecosystems. The combinatorial methodology as a powerful tool for a complex system analysis can be introduced into environmental studies by use of this new device that we are developing. Both the simplified analysis and the combinatorial method are very important for solving real environmental problems.

1. Introduction

Now we face acute environmental problems by which natural ecosystems will eventually collapse. Therefore, all scientific fields should contribute to the solution of environmental problems. Nonlinear science or complex system science are not exceptions, either. Principally, almost all environmental problems include problems related to highly complex and nonlinear systems. Therefore, the research of environmental problems from the viewpoint of nonlinear science and complex system science is very important. Natural ecosystems, in fact, have been studied as traditional topics of mathematical ecology. We have focused on eutrophicated aquatic ecosystems in which important environmental problems are present.

In eutrophicated lakes and marshes, such as Lake Kasumigaura in Japan, water bloom due to toxic cyanobacteria(blue green algae), including the genus *Microcystis*, is formed in the summer in Japan. The same is true for many other countries. In regions where the water of lakes is used for drinking, it is confounded with the treatment of the proliferated toxic cyanobacteria in the water purification process. In order to accomplish the purification of eutrophicated waters, it is very important to elucidate quantitatively the mechanism of the proliferation of cyanobacteria and predict the water quality relevant to the algal in aquatics by use of a mathematical model based on the ecological mechanism.

Some mathematical models have already been proposed[1]. These models consider not only the biological characteristics of the algae in the physical environment, such as temperature and light intensity, but also many ecological interactions. One of the major interactions in lake ecosystems is a competitive process among algae species including cyanobacteria[2]. Another important interaction is that zooplankton prey on algae[3].

In addition to these interactions, some significant ecological factors which need to be taken into consideration in the models still remain. It should be noted that the high pH value in eutrophicated lake waters is usually observed in the summer. Shappiro already pointed out the role of high pH values on the dominance of cyanobacteria qualitatively in eutrophicated lakes[2]. In this study, we focused on the role of the high pH value in eutrophicated lake waters, which may have an impact on the ecological interactions leading to cyanobacterial dominance in lakes.

It is very useful for understanding phenomena to study on natural ecosystems and environmental problems from the viewpoint of nonlinear phenomena[4]. But it is not enough for only understanding the phenomena. It is important that we use the understanding to improve an actual environment. In nonlinear science, simplified models are often used in order to extract the essence of phenomena. However, it is difficult to only use the simplified model for solving actual environmental problems. Because numerous factors and interactions can't be neglected in the ecosystems or natural environment, the realistic complex model must be used to predict a phenomenon in natural ecosystems and to control environmental problems[5].

Of course, it is impossible to include all elements in a model. But the only realistic choice for solving environmental problems is to know the characteristics of many species of organisms, interactions between them and external factors. However, quantitative knowledge about these is insufficient. In water environments, a great number of species of phytoplankton (including cyanobacteria), zooplankton and bacteria exist, and a great number of interactions between them exist. Because many of the quantitative properties of these species in aquatic ecosystems are still unknown, it is necessary to rapidly measure the properties of the species and their interactions. Therefore, we are focusing on a new methodology using the lab-on-a-chip-device for rapid measurement[6]. This device is also called micro-Total-Analysis-Systems(μ-TAS), in which micro-mechanical systems, micro-fluidic systems, and micro-electronic systems for measurement of chemical substances are fabricated on a glass base, a plastic base or a silicon base[6]. We can rapidly measure plankton and microbes using the Lab-on-a-chip-device, because we can measure small amounts of samples in parallel. Moreover we can measure one cell or a few cells, without culturing, using this system because of the small size of the measurement system. Now, we are developing the Lab-on-a-chip-device to measure activity of phytoplankton, zooplankton and another microbes in aquatic environments. At this time we will show the preliminary device we are developing.

2. Analysis on the role of pH value for cyanobacterial production-mechanism

2.1. The model equations

First of all we shall discuss the reason for the pH vale of lake water becoming high alkalinity with the proliferation of cyanobacteria[3]. When cyanobacteria takes both carbonate species HCO^-_3 and CO_2 in lake water, the pH value of the water increases over 10 in many eutrophic lakes. The concentrations of HCO^-_3 and CO_2 (H_2CO_3) in the waters decreases as a result of the rapid uptake of both carbonate species by cyanobacteria than that of dissolving of carbon dioxide into waters. Therefore, it creates an equilibrium between H^+ conjugated with HCO^-_3 and OH^- conjugated with metal cations to increase in the OH^- ion. This means waters become high alkalinity, when cyanobacteria grows in eutrophic lakes.

One of the influences is that the high pH value allows the suppression of the growth of zooplankton, viz. it may lower the predation pressure for cyanobacteria. Therefore, a growth model of cyanobacteria taken pH change in waters and predation of zooplankton into consideration was constructed as follows:

$$\frac{dA}{dt} = \mu A\left(1 - \frac{A}{K}\right) - \nu \frac{AZ}{Y_{Z/A}} - \delta_A A \qquad (1)$$

$$\frac{dZ}{dt} = \nu AZ - \mathrm{D}(C)Z \qquad (2)$$

$$\frac{dC}{dt} = K_{La}(C_0 - C) - (\mu - R\delta_A)\frac{A}{Y_{A/C}} + \{\nu A + B - \mathrm{D}(C)\}\frac{Z}{Y_{Z/C}} \qquad (3)$$

$$\mathrm{D}(C) = D_0 + \frac{10}{1 + 10^{11723(C-0.0003)}} \qquad (4)$$

,where the variables *A, Z* and *C* represent the biomass(dry weight mg L^{-1}) of the cyanobacteria, zooplankton and concentration of total carbonate, respectively. D_0 was a natural death rate at pH 7.0.

The components of these equations are expressed as follows:

In equation (1) on the cyanobacterial proliferation, there are three terms. The first term represents a logistic growth of algae with a maximum specific growth rate μ and a carrying capacity *K*. The second term represents a predation by zooplankton. ,$Y_{Z/A}$ value is the yield of cyanobacteria to the biomass of zooplankton. The last term represents the natural death of cynaobacteria. δ_A is a specific rate of natural death of cyanobactria.

The equation (2) is the formula of the growth of zooplankton. The first term represents the increase of zooplankton with growth. ν is a specific growth rate per unit biomass of cyanobacteria. The second term represents the death rate of zooplankton, that is a function of pH value. Furthermore, the pH value is a function of the total carbonate concentration *C* in waters. Therefore, in this analysis, we assumed that the specific death rate function D depended directly on the total carbonate concentration *C* in waters. D(*C*) of formula (4) is a death function experimentally determined about microflagellate *Monas guttula* as a typical predator for cyanobacteria *Microcystis*.

The equation (3) is the formula of the dynamics of total carbonates in waters. The first term represents the exchange of carbon dioxide between waters and atmosphere above the waters with the exchange rate K_{La} and the saturation concentration C_0 of total carbonates. The second term represents the net assimilation rate of cyanobacteria. Here, the parameter *R* was the coefficient for the release of carbon dioxide when the dead algae degraded naturally. Then, the $Y_{A/C}$ and $Y_{Z/C}$ value was the yield of cyanobacteria to carbon and that of zooplankton to carbon. The third term represents a release rate of carbon dioxide from the zooplankton. In this term, coefficient *B* means the release rate of carbon dioxide under the basal metabolism of the zooplankton.

2. 2 Results and discussion of the numerical analysis

The nonlinear ordinary differential equations of the cyanobacterial growth model were solved numerically using the set of parameters in Table1 (Mathematica v4.1 was used). The results could not be compared with the field observations directly, because we thought this model was a conceptual model. Nevertheless, it was thought that these results demonstrated the general features of the high pH effect of lake waters. In this analysis, several computations on the model equations were performed using parameters based on the set in Table1.

At first, specific growth rate μ of cyanobacteria was allowed to increase from 0.5day^{-1} to 1.4day^{-1}. Figure1 shows the biomass of cyanobacteria, that of zooplankton and pH values at the stationary states of the solutions plotted as functions of μ. According to the results, the biomass of zooplankton increased until μ = 0.9day^{-1}, because the biomass of cyanobacteria as a food source for zooplankton increased simultaneously. The pH values kept less than pH 8.5, until which zooplankton could proliferate in the analysis. However, the biomass of zooplankton decreased when it increased to over 1.0 day^{-1}, although the biomass of cyanobacteria increased. This result was due to pH values had gone beyond the safe value for the growth of zooplankton. The decrease in biomass of the zooplankton caused a reduction of predation pressure to the cyanobacterial population. This reduction of predation pressure caused the rapid growth of cyanobacteria. Then, the pH value became highly alkalinity rapidly by the cyanobacterial photosynthesis. The high alkaline pH values of more than 9.0 in waters led to the extinction of zooplankton in this model. It is well known that the growth of green algae and diatom can be inhibited by high alkaline pH, because both algae have less nutrient-uptake than that of cyanobacteria under this pH condition[2]. Consequently under the high pH condition, cyanobacteria such as *Microcystis* may grow favorably in comparison with other algae.

It was a very remarkable phenomenon that zooplankton died completely when the parameter μ increased more than a critical value determined by the model equations. This phenomenon is likely in non-equilibrium critical phenomena in physical systems such as laser systems or fluid systems. There is certainly a positive feedback loop process in the critical phenomena. The mechanism of positive feedback is now focused on considering population dynamics and the succession processes of organisms in ecosystems[4]. A schematic diagram of this mechanism is shown in Figure.2. Further more the phenomenon is recognized as a bifurcation phenomenon from the viewpoint of dynamical systems. Therefore we will perform a bifurcation analysis of the system.

By this mechanism, the *Microcystis* can change the surrounding aquatic factors into favorable conditions for the growth. And it is a key point of the rapid change from a species of algae to *Microcystis*. Moreover, it is supposed that the existence of the positive feedback mechanism is related to the rapid fade out of *Microcystis*. When the feedback loop is broken, the aquatic ecosystem rapidly changes to another state. By a manipulated break of a positive feedback loop, the occurrence of *Microcystis* forming water bloom might be suppressed effectively. But it is necessary to obtain a lot of information about the surrounded physical and chemical factors as well as biological interaction to make clear the mechanism of the burst proliferation and control it.

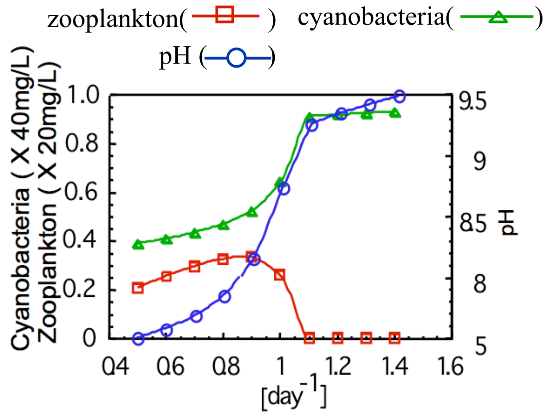

Figure1 Changes in the biomass of cyanobacteria, that of zooplankton and pH as functions of the cyanobacteral specific growth rate μ

Table1 The set of parameter for the simulation

μ	[day $^{-1}$]	0.5~1.4	$Y_{Z/A}$	0.5
K	[mg.L^{-1}]	40	$Y_{A/C}$	2.0
ν	[day $^{-1}$]	0.025	$Y_{Z/C}$	3.0
δ_A	[day $^{-1}$]	0.1	R	0.1
D_0	[day $^{-1}$]	0.2		
B	[day $^{-1}$]	0.1		
K_{La}	[day $^{-1}$]	2.0		

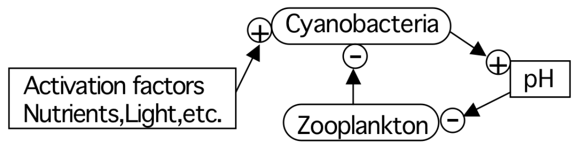

Figure2 A schematic diagram for the simple interaction of the food web. The interaction was considered with the role of pH value in the eutrophicated lakes. The feedback cycle in the food web includes double negative effects by the pH effect.

3. Lab-on-a-chip device for complex system analysis

In order to understand natural ecosystems as complex systems, in which many species and many interactions exist, we are developing on the Lab-on-a-Chip device[6].

Now, we are developing the Lab-on-a-chip-device to measure activity of phytoplankton, zooplankton and another microbes in aquatic environments. In figure 3, we will show the concept of the device we are developing. For real system, we install sensor systems to measure cell activity[7]. The device has many microchamber arrays in which cell activities will be measured. And some different medium will be provided thorough microchannels.

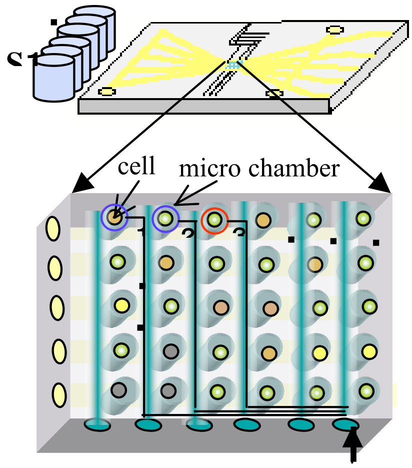

Figure3 The concept of a Lab-on-a-chip device for measurement microbes in aquatic environment.

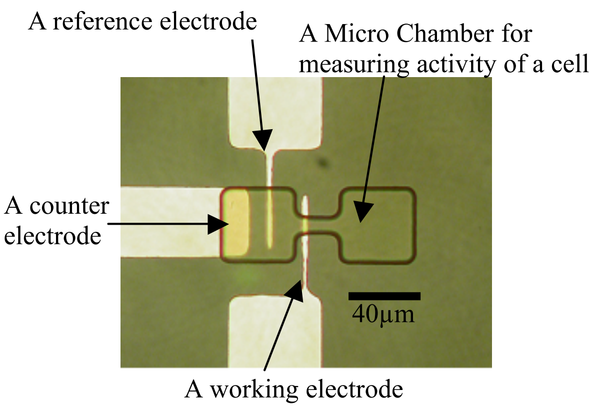

Figure4 The photograph of a Lab-on-a-chip that we are developing.

Figure 4 shows a microscopic photograph of the device which we are developing. The device was made based on a microfabrication process of polymer[6]. In the device the three micro Pt electrode are made by photolithography. We can measure oxygen production from algal cells in the microchamber by a microamperometric method[8].

The device will make it possible to rapidly measure many properties of many species of plankton and microbes in real ecosystem. We can obtain many parameter values at the same time[7]. We can precisely analyze on complex ecosystems using the parameters. The combinatorial methodology is a very effective to study on a complex system. The new device is a best tool for combinatorial experiments of environmental microbiology and microbial ecology[7]. Both the simplified nonlinear analysis and the combinatorial method using new devices are very important for solving the real environmental problem.

4. Conclusion

1) We analyzed a vast proliferation of toxic cyanobacteria in an eutrophicated lake using a nonlinear model equation of population dynamics determined. In the nonlinear model equation of cyanobacterial we used, we focused on the interaction of rise of the pH and pressure from the zooplankton.

2)The rise of pH is according to the proliferation of cyanobacteria. This equation was numerically solved and the vast proliferation of cyanobacteria was determined as a bifurcation phenomenon. However it is not sufficient to only use a simple and conceptual model analysis to tackle a real environmental problem.

3) We are focusing on a new methodology using the Lab-on-a-chip-device for rapid measurement. We are developing the Lab-on-a-chip-device to measure activity of phytoplankton, zooplankton and another microbes in aquatic environments.

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