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Mathematical model approach to understand the ecological effect under chronic irradiation

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Abstract. Although aim of the environmental protection is conservation of ecosystem, there are only a few studies focusing on the effect of radiation on ecosystem. To understand the ecological effect of irradiation, microbial ecosystem, "microcosm", which contains minimum components of ecosystem such as producer, consumer and decomposer, is useful because the natural ecosystem is too complex. The microcosm consists of three species, i.e. *Euglena* (producer), *Tetrahymena* (consumer), and *E. coli* (decomposer). The mathematical model and computer simulation model were also developed to understand the mechanism of ecological interaction using the results of acute exposure experiments of the microcosm, and we predicted *Tetrahymena*, which is the most radio-resistant among the constituent species, would be most sensitive in the chronically irradiated microcosm as a result of an indirect effect due to population decrease in *E. coli*. Recently we started chronic exposure experiments. The microcosms were irradiated with γ-rays at dose rate of 1.2Gy/day, 5Gy/day, 10Gy/day and 23Gy/day. From preliminary results, we found that the prediction from the models was different from the experimental results. Therefore, in this study, we improved our mathematical model and discuss the difference between the model and experiments.

1. INTRODUCTION

Almost all of researches which are studied about the impact of radiation to the environment or ecosystem are focused on the individual level and are not considered interaction of inter-species or intra-species. However, there are underlying large difficulty in studying the natural ecosystem directly, because the real ecosystem consists of huge species and construct complex interaction network between the species. Microcosm is the one of the most useful tool to study ecosystem, which consists of minimum component of natural ecosystem and can observe and simulate interaction among the species in laboratory level. We have been studying the effect of the irradiation to ecosystem using the microcosm which developed by Kawabata et al. [1]. The microcosm consists of three species, Flagellate algae *Euglena* as a producer, ciliate protozoa *Tetrahymena* as a consumer and bacteria *Escherichia Coli* as a decomposer. The interaction between the species in the microcosm is summarized in Figure 1. The microcosm is maintained by photoenergy which *Euglena* fixed by photosynthesis, *E. coli* consumes the products which released from *Euglena*, and *Tetrahymena* grazes *E. coli* directly [1–6].

The 50% lethal doses (LD_{50}) of acute exposure of single species have been reported in previous study [2], *E. coli* is the most sensitive species and *Tetrahymena* is the most resistant species to γ-irradiation. However, in the three species co-cultured microcosm, the extinction order is *E. coli* (the most sensitive species), *Tetrahymena*, and *Euglena* (the most resistant species). This result did not due to change the radiation sensitivity of *Tetrahymena* but caused indirectly by extinction of *E.coli*.

From the experimental results of acute irradiation, we developed the mathematical models and analyzed about the situation of chronic exposure [7, 8]. From the analysis of the models, we found that *Tetrahymena* who is the most radio-resistant species in single culture is the most radiation sensitive species and *E. coli* is the resistant to radiation rather than *Tetrahymena*. This result is robust when the interaction of the species is simple prey-predator type.

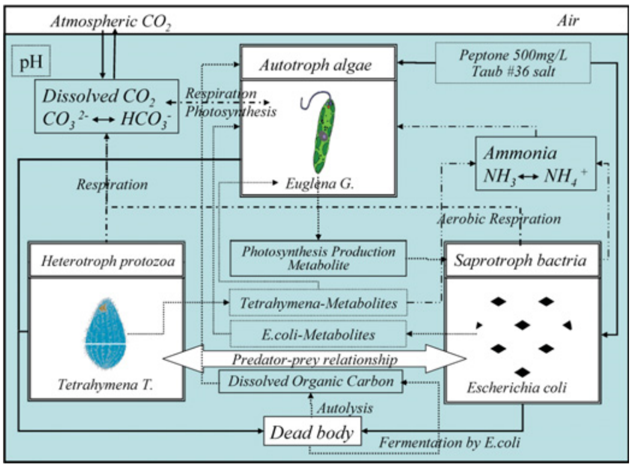

Figure 1. Schemes of interrelationships among microorganisms and constituent elements in Kawabata-microcosm taken from [1–5].

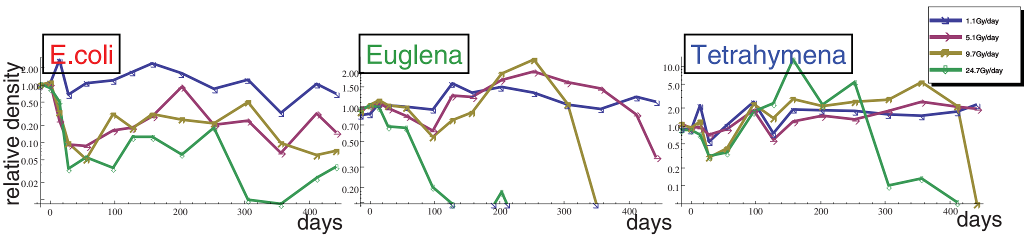

Figure 2. Summary of the experimental results of the chronically irradiated microcosm. The horizontal axis is time since onset of exposure, and vertical axis is the relative population density to the control.

Figure 2 showed the summary of the results of chronic exposure to the microcosm [8]. The microcosms were irradiated with γ-rays at dose rate of 1.2Gy/day, 5Gy/day, 10Gy/day and 23Gy/day. From the experimental results of chronic exposure, population density of the E.coli decreases with dose rate, and Tetrahymena seems almost constant or slightly increased with dose rate increasing. These results are different from the model prediction, and imply that the interaction between *Tetrahymena* and *E.coli* is not simple prey-predator relationship. One explanation for this difference is that predation resistant phenotype existed in *E. coli* population. Nakajima and Kurihara [9] reported that the *E. coli* which has very long body length observed when *E. coli* is exposed to predation pressure. Therefore, in this study, we improved our model to include the predation resistant phenotype in *E.coli* population.

2. THE MODEL

We consider the *E. coli* have two phenotypes, normal phenotype and predation resistant phenotype, and we assumed those phenotypes were genetically distant. We assumed the resistant phenotype of *E. coli* escape from the predation, however, the growth rate of the resistant phenotype is lower than that of normal phenotype. We consider the population density of the normal phenotype, N, is increased by consuming the photosynthesis products from *Euglena* (P) and decreased by predation. On the other hand, population density of resistant phenotype, L, also increases with consuming the products, however, decrement term by predation is omitted because of its resistant body form. The dynamics of

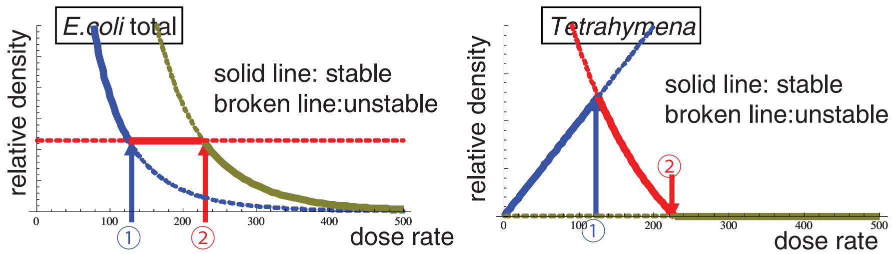

Figure 3. Summary of the analytical results of the model.

the system described as follows:

$$\begin{aligned}\dot{E} &= r_E E(1 - E/K) - \alpha_E E \\ \dot{P} &= sE - a(N + L)P \\ \dot{N} &= r_N a N P - bNT - \alpha_N N \\ \dot{L} &= r_L a L P - \alpha_L L \\ \dot{T} &= r_T bNT - \alpha_T T\end{aligned} \tag{1}$$

where E, N, L and T denote population density of *Eulgena*, normal phenotype of *E. coli*, predation-resistant phenotype *E. coli* and *Tetrahymena*, respectively. r_x is the intrinsic growth rate of species x ($x = E$, N, L or T), K is the carrying capacity of *Euglena*, s is the release rate of photosynthesis products from *Euglena*, a is the predation rate of *E. coli*, b is the predation rate of *Tetrahymena*, and α_x is the additional mortality of species x due to the irradiation. According to the LD_{50} value of single species, we assumed the radiation sensitivity of *E. coli* is the highest in the microcosm and the lowest is *Tetrahymena*.

3. RESULTS AND DISCUSSION

From the analysis of equation (1), we found four equilibria in the system except a trivial equilibrium which is all species extinguished. We analyzed local stability of the equilibria and found that two or more stable equilibria could not coexist. We also found that the equilibrium which is coexisting of *Euglena* and resistant phenotype of *E. coli* was always unstable since we assumed that the growth rate of resistant phenotype is lower than the normal phenotype. Typical results of the model were summarized in Figure 3. The total population density of two phenotype in *E.coli* decreases with increasing the dose rate until threshold 1 which predation resistant *E. coli* goes extinct at. In this dose rate region, population density of Tetrahymena increases, because the predation resistant *E. coli* decreases with increasing dose rate, so that the normal phenotype obtains more products from the Euglena and increases the population density. Increment of the density of the normal *E. coli* results the increment of the density of predator species, *Tetrahymena*, and apparent population density of normal phenotype is balancing the increment due to gain of the products from Euglena and decrement by increasing predation pressure.

When the dose rate is larger than the threshold 1 and lower than the threshold 2, population density of *E. coli* stays constant, whereas *Tetrahymena* density monotonically decreases and equals to 0 at threshold 2. In this region, the relationship between *E.coli* and *Tetrahymena* is again simple prey-predator model, therefore, the interpretation of the result is the same as previous our model.

From the results of the present model, in spite of the simplification of the model structure, the model qualitatively explained the experimental result. Therefore, emergence of the predation resistant phenotype in *E. coli* would have important role when radiation exposed chronically to microcosm.

However, interaction among the species is still complex even if the microcosm consists of only three species. To understand the real dynamics of the system, more realistic modeling approach such as individual based model could show other cutting edges.

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