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A Computational Study and its Application of Strategic Mating Behavior in Frogs

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Abstract: We focus on two behavioral strategies of male frogs for mating. Namely, there are two choices for males to vocalize calls to attract females (calling behavior), or to stay silent and attempt to intercept the females (satellite behavior). To theoretically examine the efficacy of these strategies, we propose a computational model and numerically evaluate two factors of the efficiency of mating and the energy consumption. Our results demonstrate that calling males mate more successfully than satellite males. In addition, the more the ratio of calling males is, the less time males spend until mating. In contrast, satellite males can save their energy more efficiently than calling males. Consequently, a trade-off between the efficiency of mating and energy saving is suggested. Finally, we discuss a possibility of applying the mating behavior to target searching problem using multiple robots.

Keywords: Animal behavior, Mating strategy, Mathematical modeling, Biologically inspired technology

1 INTRODUCTION

Many studies have been performed on biologically inspired technology, which is the application of a superb structure and behavior of animals. For example, there are an adhesive tape inspired by the structure of a volar surface of gecko and an antireflection film inspired by the structure of eyes of moth [1]. While many studies have been conducted on such technologies imitating the structure of animals, there are less studies imitating the behavior of animals. Because animals have acquired flexible and superb behavior during the process of evolution, it would be worth studying animal behavior from the viewpoints of understanding behavioral mechanisms in animals and also inspiring new techniques.

In this study, we focus on the mating behavior of frogs. In general, male frogs vocalize calls to attract female frogs [2]. While the calling behavior is a quite effective action to attract female frogs, some male frogs intentionally stay silent in the vicinity of a calling male and attempt to intercept female frogs [2]. This is known as *satellite behavior* that allows male frogs to reduce energy consumption while having a chance for mating, and is often observed in the situation that many males make a chorus with a high density [2]. Thus, male frogs have a chance to select calling state or satellite state depending on the surrounding situation such as the density of male frogs. Subsequently, it is likely that the ratio of two behavioral types of male frogs is a key factor establishing high performance in mating and energy saving in the aggregation of frogs.

In order to theoretically examine the efficacy of such a choice of behavioral types, we first propose a computational model using flowcharts that describe two behavioral types of male frogs as well as one type of female frogs (Section 2). Then, we perform numerical simulations using the proposed model, and analyze the result in terms of success rate of mating, the required time for mating, and the energy consumption until mating (Section 3).

2 PROPOSED MODEL

2.1 Target species

In this study, we focus on the behavior of green treefrogs (*Hyla cinerea*) for the following reasons.

- It is observed that green treefrogs select satellite behavior or calling behavior. In addition, previous study indicates that most male frogs rarely switch between the two behavioral types on a single night in this species [3]. This feature allows us to model the mating behavior of male frogs with a simple computational model.
- Previous study already estimates the ratio of behavioral types (calling, satellite, or non-calling) through behavioral observations at the breeding site [3]. The data allows us to utilize the parameters of the real frog data.

2.2 Overview of our model

We propose a computational model that describes the calling behavior and the satellite behavior of a male frog, and the foraging behavior of a female frog by using separate flowcharts (see Figs. 1, 2 and 3). It is assumed that the model frogs select a state based on visual information and acoustic information, and then behave according to the rule of their state for T [s]. Here, we define visual information and acoustic information as follows:

- Visual information: We assume that each frog looks at neighboring frogs within a close distance and acquires the information of their positions and types (i.e., male or female, and calling state or satellite state).
- Acoustic information: We assume that each frog hears the calls vocalized by male frogs and can estimate the direction of the nearest calling male frog.

2.2.1 States of a male frog (type 1)

A male frog (type 1) is modeled as an individual that mainly takes calling behavior while intermittently staying silent. Finally, he mates with a female when she is attracted to himself. In our model, the male frog (type 1) is assumed to take the following states.

- Chorus state: In general, male frogs produce successive calls and then stay silent for a certain amount of time [4]. Based on this feature, we model that a male frog (type 1) intermittently switch between the calling state and the silent state every T [s].
- Moving state: A male frog (type 1) moves away from another calling male frog when they exist in the vicinity with each other.

2.2.2 States of a male frog (type 2)

A male frog (type 2) is modeled as an individual that intentionally stays silent in the vicinity of a calling male frog (type 1) so as to intercept a female frog attracted to the calling male frog. In our model, the male frog (type 2) is assumed to take the following states.

- Satellite state: When a male frog (type 2) recognizes a male frog (type 1) in his visual range, he stays on the position and waits for an opportunity to intercept a female frog that is attracted to the calling male frog.
- Moving state: A male frog (type 2) approaches the nearest calling male frog utilizing his acoustic information.

2.2.3 States of a female frog

A female frog is modeled as an individual that is attracted to a calling male frog (type 1) and attempt to mate with him. In our model, a female frog is assumed to take only the following state.

- Moving state: A female frog approaches the nearest calling male frog utilizing acoustic information so as to mate with him.

2.3 Mathematical modeling

2.3.1 Modeling of a male frog (type 1)

We assume that a male frog (type 1) chooses its behavioral type according to the flowchart of Fig. 1. In our model, a male frog (type 1) doesn't search for female frogs actively but attempts to attract a female by producing sounds. First, we assume that he acquires both of visual information and acoustic information. In general, male frogs vocalize calls not only to attract female frogs, but also to keep their territory [2]. Based on this feature, we assume that, if a male frog (type 1) recognizes another calling male frog (type 1) in a close distance, he moves away from him. Otherwise, he takes chorus state and then waits for female frogs.

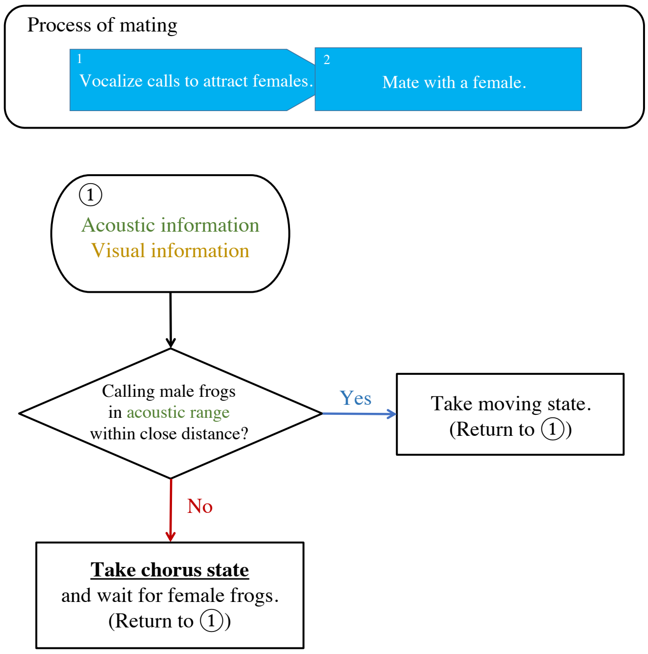

Fig. 1. Behavioral model of a male frog (type 1).

2.3.2 Modeling of a male frog (type 2)

We assume that a male frog (type 2) chooses its behavioral type according to the flowchart of Fig. 2. In our model, a male frog (type 2) takes satellite state in the vicinity of a calling male frog (type 1), and then attempts to intercept a female. First, we assume that he acquires visual information and acoustic information as well as a male frog (type 1). Then, if he can recognize a female frog in his visual range, he mates with the female frog. If he cannot look at a female frog, he utilizes the visual information so as to recognize a calling male frog. When he can recognize a calling male frog, he takes satellite state in the vicinity of the calling male frog and aims to intercept a female frog attracted to him. If a male frog (type 2) cannot recognize both of a female frog and a male frog (type 1) in visual range, he utilizes the acoustic information produced by other male frogs (type 1). When he can recognize calls, he moves toward the nearest calling male frog. In the case that a male frog (type 2) cannot recognize any frogs from the visual information and acoustic information, he does nothing and just keeps staying on the same position.

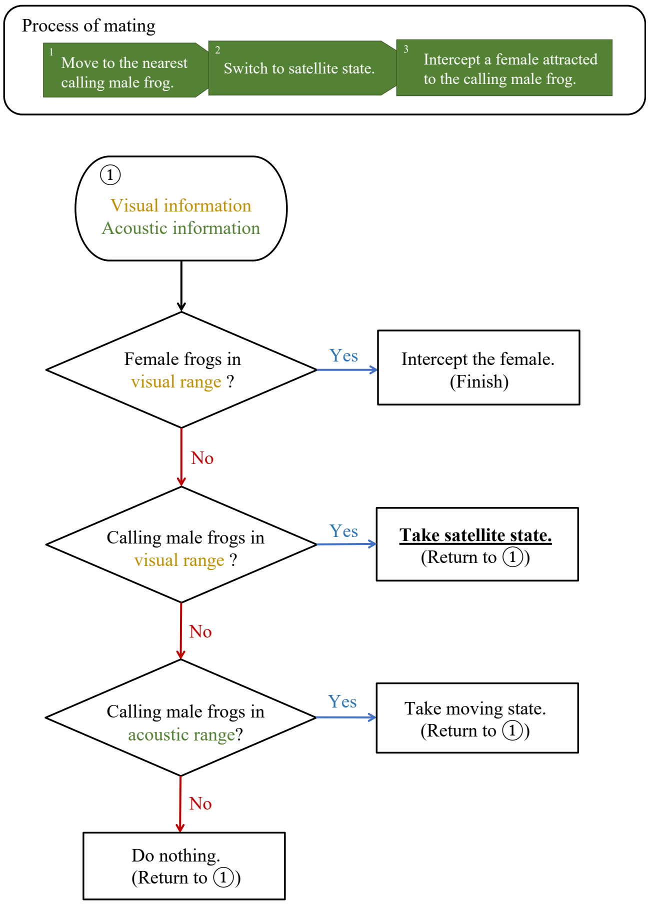

Fig. 2. Behavioral model of a male frog (type 2).

2.3.3 Modeling of a female frog

We assume that a female frog chooses its behavioral type according to the flowchart of Fig. 3. In our model, a female frog searches for male frogs basically depending on their calls. First, she acquires visual information and acoustic information. If she can recognize a calling male frog (type 1) due to acoustic information, she moves toward the nearest calling male frog. Next, if she finds a calling male frog (type 1) in visual range, it is assumed that she completes mating. Otherwise, she does nothing and just keeps staying on the same position. Note that there is a case in which a female frog is intercepted by a male frog (type 2).

2.4 Energy consumption

We assume that male frogs consume their energy when they are in calling state or moving state. First, when a male frog (type 1) in calling state vocalizes a single call, we assume that he consumes energy at E_1. Second, when a male frog (type 1 and type 2) in moving state hops 1 [m], we assume that he consumes energy at E_2.

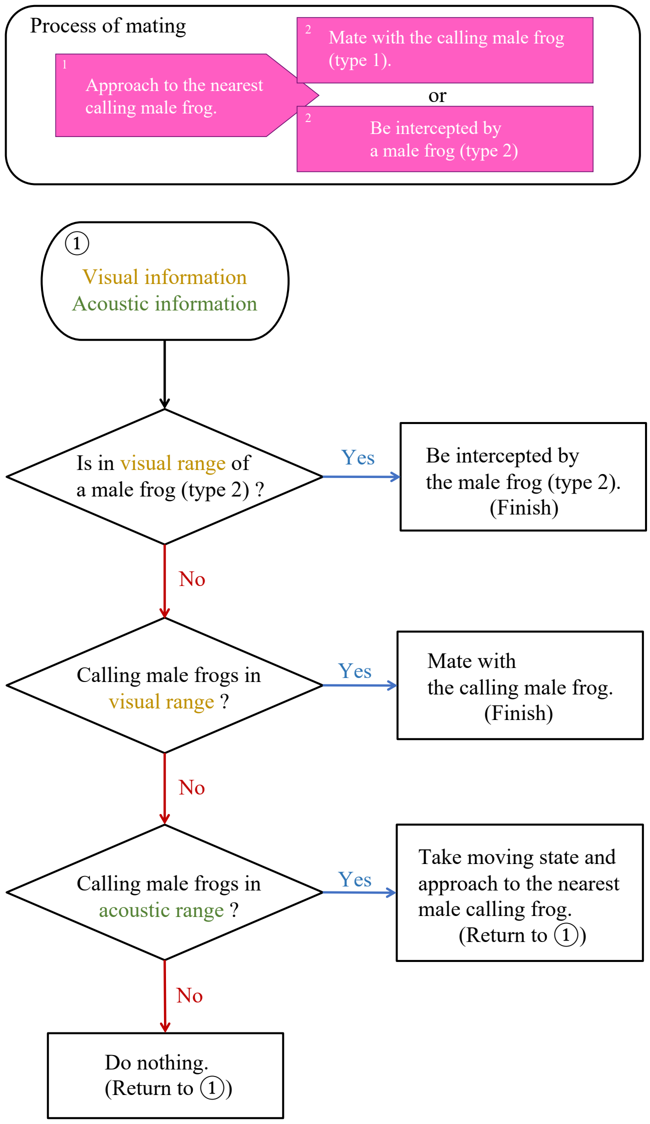

Fig. 3. Behavioral model of a female frog.

3 NUMERICAL SIMULATIONS

3.1 Settings

We perform the numerical simulation of our model with 50 frogs (45 male frogs (type 1 and type 2) and 5 female frogs). In this numerical simulation, the initial positions of male frogs are randomly set in the field of 20 [m] × 20 [m]. When all female frogs mate with the male frogs, the numerical simulation is finished.

Next, we fix some parameters of this model as preciously as possible based on empirical data.

- In this study, we assume that a model frog switches its behavioral type every T [s]. While we focus on the behavior of green tree frogs (Section 2.1), we could not find the studies related to this parameter. Therefore, we fix this value as $T=30$ following the study on chorus duration in other species of tree frogs (*Hyla japonica*) [5].
- As for call rate, previous study shows that male green tree frogs vocalize about 80 calls in 60 [s] [4]. Based on this feature, we assume that male frogs (type 1) vocalize 40 calls in $T=30$ [s] when he is in calling state.
- As for moving distance, Zug [6] experimentally evaluated hopping distance in various frog species including green tree frogs. Based on this study, we assume that the model frogs move 40 [cm] at one hop.
- As for frequency of hopping, we could not find the studies on green tree frogs. Therefore, we follow the study on other species of tree frogs (*Litoria chloris*) [7], and then estimate this parameter as the model frog in moving state hops one time every 30 [s].

With respect to other parameters of our model, we fixed the values not based on the previous studies but to be consistent with our intuition that is based on our observations of multiple frog species, as follows:

- We assume that male frogs (type 1) attempt to keep a distance at least 1 [m] for each other if they are in moving state.
- We assume that male frogs (type 2) take satellite state if he is within 20 [cm] from a male frog (type 1).
- We set visual range of the model frogs as 40 [cm].
- Various experimental studies have shown that a male frog loses a large amount of weight when joining choruses [4]. This indicates that the calling behavior of a male frog causes severe energy consumption. Based on these features, we fix E_1 as 1, and then fix E_2 as several types of parameter value, 1, 5, 10 and 40. These parameter values correspond to the situation that male frogs in calling state consume more energy than male frogs in moving state. Namely, even when E_2 is set as the maximum value of 40, energy consumption of male frogs in moving state during $T=30$ [s] is $E_2 \times 0.4$ [m] = 16 that is smaller than as the energy consumption of a male frog (type 1) in calling state (Note that the energy consumption in calling state during $T=30$ [s] is 40.)

Finally, we vary the ratio of male frogs (type 1 or type 2) and then perform numerical simulations 100 times in each ratio while randomizing initial condition on the spatial distribution of male frogs. It should be noted that Gerhardt et al. reported that the ratio of the behavioral types in male green tree frogs was almost 8:1 between calling males and satellite males [3], corresponding to the ratio 8:1 between male frogs (type 1) and male frogs (type 2) in this study.

3.2. Representative case of numerical simulation

Fig. 4 shows an example with 30 male frogs (type 1), 15 male frogs (type 2) and 5 female frogs. In this figure, each icon represents the position and the type of each frog. Fig. 4 demonstrates that all female frogs finally succeeded in making pairs.

3.3 Success rate of mating per a male frog

Fig. 5 shows the success rate of mating per a male frog. Here, we calculate the success rate by dividing the number of male frogs (type 1 or type 2) mating with a female by the number of all the male frogs (including both type 1 and type 2). In Fig. 5, we emphasize the ratio of male frogs estimated from empirical data [3] by a red arrow. In addition, symbols "∗" give the mean of success rate in each ratio. It is demonstrated that the success rate of mating per a male frog (type 1) is higher than that of a male frog (type 2) regardless the ratio of the behavioral types.

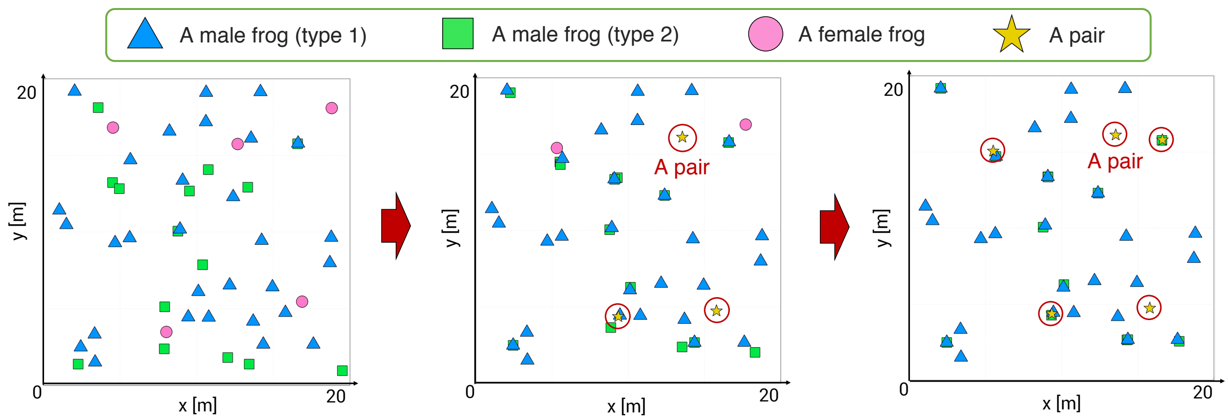

Fig. 4. Snapshots of the numerical simulation of our model. This figure demonstrates that all the female frogs finally succeeded in making a pair.

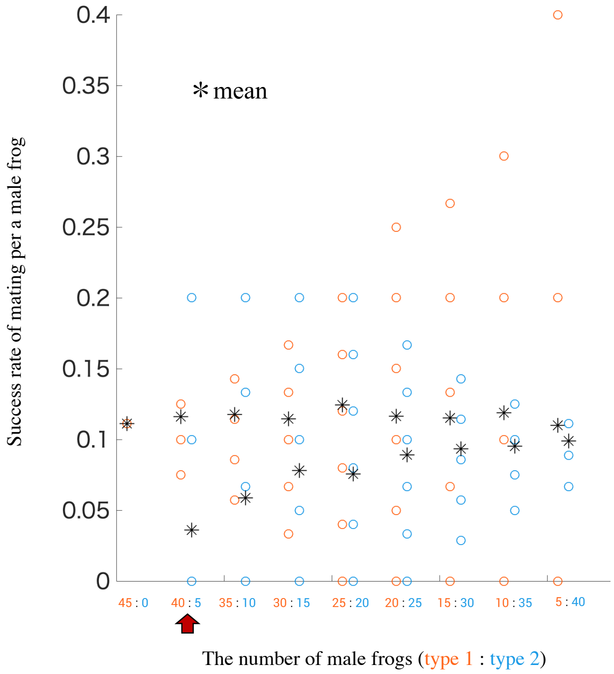

Fig. 5. Results of numerical simulation on success rate of mating per a male frog.

3.4 Required time until making pairs

Fig. 6 shows the required time for mating that is calculated as the mean of time that each male frog spends until mating. It is demonstrated that the less the ratio of male frogs (type 2) is, the less required time male frogs spend until they accomplish mating. In our model, when all male frogs are type 1, all female frogs need the shortest time to make pairs.

3.5 Energy consumption until mating with female frogs

Fig. 7 shows energy which male frogs consume until mating with female frogs. We perform numerical simulations for several types of parameter value (i.e., E_2 = 1, 5, 10 and 40). Then, we calculate the energy consumption as the mean of energy that male frogs (type 1 or type 2) consumes until mating. Fig. 7 indicates that male frogs (type 1) consume more energy than male frogs (type 2) does as for E_2 = 1, 5, or 10. On the other hand, when E_2 is set as 40 and the number of male frogs is set as 5:40 between type 1 and type 2, male frogs (type 2) consume the similar amount of energy with male frogs (type 1).

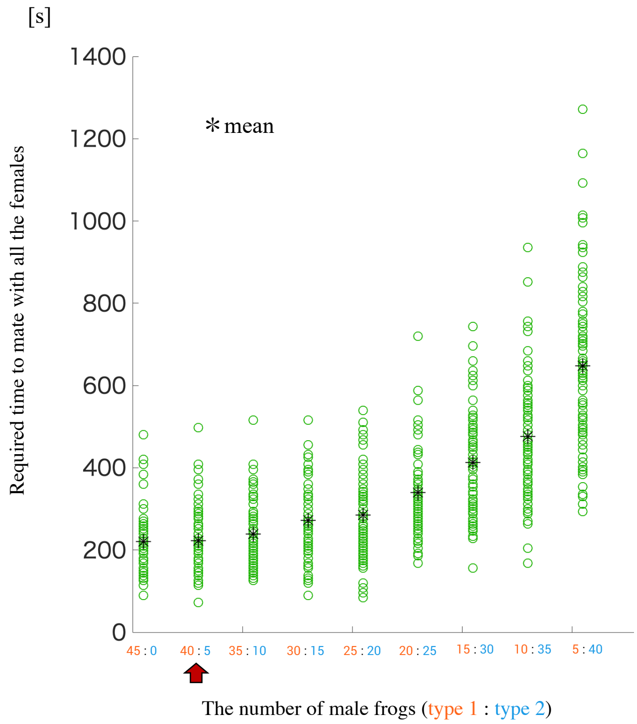

Fig. 6. Results of numerical simulation on required time for mating. We emphasize the ratio of male frogs estimated from empirical data [3] by a red arrow. In addition, symbols "∗" give the mean of required time in each ratio.

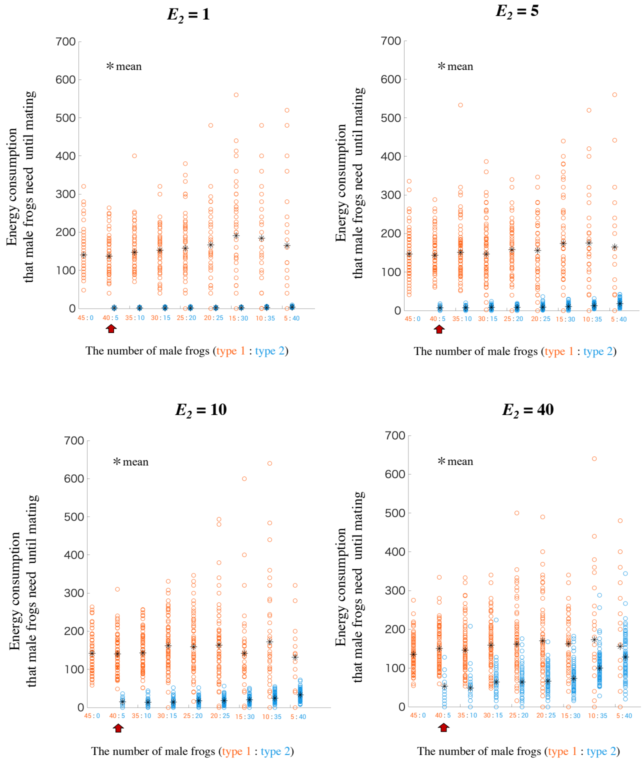

Fig. 7. Results of numerical simulation on energy that male frogs consume until mating for several types of parameter value (i.e., E_2 = 1, 5, 10 and 40). We emphasize the ratio of male frogs estimated from empirical data [3] by a red arrow. In addition, symbols "∗" give the mean of required time in each ratio.

4 CONCLUSION

In this study, we focus on two behavioral types of male frogs in mating (i.e., calling behavior and satellite behavior). To theoretically examine the validity of the two behavioral types, we proposed a computational model and then performed numerical simulations. Our results suggest that calling male frogs mate with female frogs more successfully than satellite male frogs. In addition, the more the ratio of calling male frogs is, the less the required time until mating is. In contrast, it is suggested that satellite behavior of male frogs can reduce energy consumption of the whole system, indicating the trade-off between calling behavior and satellite behavior.

As for the ratio estimated from empirical data [3], success rate of mating in satellite male frogs is the lowest among all the ratios of two behavioral types, but they save their energy more efficiently than calling males even when E_2 is set as 40. In addition, male frogs can reduce required time to mate with female frogs compared to other ratios.

In this study, we set the duration of silent state in male frogs (type 1) as T [s] as with the duration of calling state. In our model, male frogs (type 1) do nothing in silent state. Given that male frogs (type 2) and female frogs take moving state in accordance with calls vocalized by male frogs (type 1), male frogs (type 2) and female frogs presumably do nothing when male frogs (type 1) are in silent state. Therefore, it is likely that the duration of silent state doesn't affect the result of numerical simulation as for the success rate of mating, the required time for mating, and the energy consumption until mating.

In this study, we basically assume the behavior of green treefrogs, which rarely switch between calling behavior and satellite behavior on a single night [3]. On the other hand, it is known that some species of male frogs flexibly switch between calling state and satellite state depending on their surrounding situation (i.e., density of male frogs in a breeding state) [4]. As the future work, we should extend our model so as to describe the switching between calling behavior and satellite behavior.

As the application of the mating behavior of frogs, we focus on the engineering system such as target search by multi-robot systems. In such a system, it is necessary to improve searching efficiency and also reduce energy consumption of the entire system. If we can construct a simple computational model reproducing the behavioral mechanism of male frogs, we would apply the model to the engineering system including the control system of autonomous decentralized mobile robots.

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