Modeling “Info-chemical” Mediated Ecological System by using Multi Agent System

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Abstract: We model and simulate an ecological system, where each agent (plants, herbivores and carnivores) communicate with each other by using communication languages of chemical volatiles (info-chemical signals). This info-chemical signals are produced by plants when they are suffered from feeding damage of herbivores and natural enemy (carnivores) of the herbivores are attracted by the signal. In this ecological system, since carnivores learn the signal and trace it, plants try to endure the feeding damage until the population of herbivores become large and enough herbivores can supply for the carnivores, otherwise carnivores are not to be attracted by the signal and try to explore more valuable signal. However, it has reported that, some mutated plants produce chemical signals soon even if there are few or no herbivores and attract carnivores (cry wolf plants). We model the ecological system which cry wolf plants by using the MAS. without geographic space and with geographic space. And we confirm that in the both types of models, in order to escape from cry wolf plants, “honest plants” produce different types of signals so various types of signals emerge. Interestingly, in the system with geographic space, if there is a “colony” of cry wolf plants then signal does not evolve and honest signal and cry wolf signal can coexist.

1 CHEMICAL ECOLOGY, ECOLOGICAL SYSTEMS WITH INFO-CHEMICAL SIGNALS

In the science of (theoretical) Ecology, plants have been considered as “resources” of the food chain in the ecological system, where herbivores feed plants and carnivores feed herbivores. Hence ecological systems have been described as interactions between herbivores and carnivores such as Lotoka-Volterra model (Lotoka, 1910);

$$\dot{X} = aX - bXY, \quad (1)$$
$$\dot{Y} = bXY - cY, \quad (2)$$

where X is the population of herbivores and Y, carnivores.

However in the Chemical Ecology (Dicke and Takken, 2008), it has turned out that plants are not just resources but participating in the ecological system as “a player”; they cannot run away or remove herbivores directly but they can indirectly protects themselves by attracting herbivores’ natural enemy (carnivores) by producing signals; when plants are suffered from feeding damage, they produce volatile chemicals as “SOS signal” and attract natural enemies. Plants are able to produces about twenty kinds of signals properly and attract appropriate natural enemy according to the types of herbivores (Dicke and Takken, 2008). Carnivores learn the signal and explore herbivores by tracing the signals. Hence plants endure the feeding damage until enough herbivores can supply for the carnivores otherwise carnivores learn that the signal is not useful and they are not to be attracted by the signal and explore more valuable signal (Dicke and Takken, 2008). In contrast, it has been reported that some mutant plants produces ’cry wolf’ signals; such mutant plants produce large amount of chemicals when they suffered small feeding damage by a few herbivores. Such cry wolf plants produce the same chemical as honest plant producing chemicals (Shiojiri et al., 2010).

Shiojiri et. al. reported that “the composition of the herbivore induced volatiles show little change with the number of herbivores inflicting damage to the plant, but the amounts of volatiles and the responses of the enemies increase significantly. Signal quan-

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tity may therefore provide information to the enemies about herbivore abundance." so such plant signals is called 'honest' signal (Shiojiri et al., 2010)."

In the case when most of the plants emit honest signal, mutant plants (cry wolf plants) can gain protection from herb-ivory, because visited carnivores will remove herbivores already present. However the number of herbivores in the cry wolf signaler are a few for carnivores they learn such signal is not useful. As (Sabelis et al., 2011) point out, when a honest signal has been commonly used, cry wolf plants can take advantages to use the signal and may increase its population. However, carnivores will learn the signal as "dis-honest" signal and carnivores may not be attracted by the signal very much. So in order to keep on attracting carnivores, honest plants have to produce "new-and-honest" signals. Some theoretical models predict that co-evolution of signals will emerge in this system (Sabelis et al., 2011; Jansen and van Baalen, 2003).

2 METHOD OF MODELING AND SIMULATION

We model and simulate the ecological system by using two types of systems; system without / with geological space. In the system without geological space, we regard the system as "chemical reactions," where each agent is chemical substance and reacts with each other by reaction rule; such a MAS is called the *Artificial Chemistry* (Dittrich et al., 2006). And the system with geological space is composed of the two dimensional Cellular Automaton.

2.1 Artificial Chemistry, Abstract Rewriting System on Multisets, ARMS

Formally, an Artificial Chemistry, AC can be defined by a triple (A, R), where A is the set of molecules, R is a set of reaction rules representing the interaction among the molecules (Dittrich et al., 2006). Various ACs have been proposed and applied in modeling and simulation of complex systems (Dittrich et al., 2006). In this study, we use a model of AC, Abstract Rewriting System on Multisets, ARMS (Suzuki et al., 1996). ARMS have been used on modeling and simulation of non-linear chemical reactions (Suzuki et al., 2001), Systems Biology of the cell (Suzuki et al., 2001), a model of Origin of Life (Suzuki et al., 2001), Social Systems and so on.

In ARMS a chemical solution is a finite multiset of elements denoted by symbols from a given alphabet, $A = \{a, b, \ldots,\}$; these elements correspond to *molecules*. A reaction rule is a pair of two multisets, l, r and it rewrites a multiset, mc; if the multiset l is included by the multiset then l is removed from the mc and r is merged with it, so a rewriting is expressed as $mc - l + r$, where "+ and -" are addition and deletion on a multiset.

2.2 How does *ARMS* Work?

Example. We give R = { a,a,a $\rightarrow$ c : r_1, b $\rightarrow$ d : r_2, $c \rightarrow e : r_3$, $d \rightarrow f, f : r_4$, $f \rightarrow g : r_5\}$. and assume that set the initial state as $\{a, a, b, a\}$. In this example, the reaction rules are applied in parallel (the strategy of applying rules is not only limited in parallel but also rules can be applied rules in sequential or maximally parallel). Figure 1 illustrates a sequence of re-

$\{a,b,a,a\}$	$\subseteq a, b$
$\downarrow$	(r_1, r_2)
$\{c,d\}$	$\subseteq c, d$ (the left hand side of r_3, r_4)
$\downarrow$	(r_3, r_4)
$\{e, f, f\}$	$\subseteq f$ (the left hand side of r_5)
$\downarrow$	(r_5)
$\{e,h,h\}$	There are no rules to apply, so it reaches the *halt* state

Figure 1: Example of *ARMS* reaction steps

action steps, For $\{a, a, b, a\}$, r_1 and r_2 are applied and it is transformed into $\{c, d\}$ and r_3 and r_4 rewrite it to $\{e, f, f\}$; no rules can rewrite it so rewriting halts.

3 MODEL WITHOUT GEOGRAPHIC SPACE

It has been reported that every honest plant produces almost same quantity of HIPV and threshold of the population of herbivores for start producing HIPV almost the same (Dicke and Takken, 2008; Shiojiri et al., 2010). Hence we can estimate the degree by feeding damage by herbivores based on the quantity of the HIPVs. So we define the biomass of plants, P as $P - \Sigma H_i$, where H_i is the total quantity of every HIPVs; if the quantity of HIPVs are small, there are few herbivore and, large quantity of HIPVs indicates there are many herbivores.

The model is composed of honest signal, h_i, dishonest signal, c_i and a carnivore which is attracted by h_i or w_i; where the suffix "i" indicates the type of chemical profile of HIPV. Plants produce h_i and the carnivore is attracted and remove herbivores. When the population of honest signal increased, dis-honest signal of it emerges and if a carnivore is attracted by the dis-honest signal, it learns the signal is dis-honest and does not to be attracted by the honest signal. Hence, if the dis-honest signals increased, honest plant produces different chemical profile of HIPV. Honest plants can not know, how many dis-honest signals are produced, however if they can not produce different type of HIPV and attract carnivores, they may go extinct. Hence, if the honest plants survive under the large quantity of dis-honest signals, it indicates that honest plants can produce different type of HIPV. On the other hand, when the quantity of dis-honest signals is small, if a honest plant produces different type of HIPV, carnivores may not to be attracted to the new HIPV, because they do not have to learn it is dis-honest signal (in fact, it is not dis-honest signal because of the population of dis-honest signal is low).

Hence when the the quantity of dis-honest signal is large, if the honest plant using the same chemical profile as dis-honest signal is mutated and can produce new honest signal and attract carnivores increases its population, therefore it can be regarded as if the population of dis-honest signal increases, there emerges new honest signal. In this model, the probability of emergence of new HIPV is defined as

$$\frac{\Sigma h_i}{\Sigma(h_i + w_i)} > \tau,$$

where h_i indicates the honest signal of type i and w_i, the dis-honest signal of type i and τ is the threshold value of emerging the new type of HIPV.

The model is composed of following reaction rules;

$$\begin{aligned}
h_i &\overset{k_1}{\to} h_i, h_i(r_1),\\
h_i &\overset{k_3}{\to} c_i, h(r_2),\\
c_i, h_i &\overset{k_2}{\to} c_i(r_3),\\
h_i &\overset{k_5}{\to} w_i, h_i(r_4),\\
c_i, w_i &\overset{k_6}{\to} w_i(r_5),\\
w_i &\overset{k_7}{\to} \perp(r_6),\\
c_i &\overset{k_4}{\to} \perp(r_7),
\end{aligned}$$

where r_1 expresses the population growth of herbivores; as the population of herbivores is increased, the quantity of HIPV is also increased. r_2 expresses the HIPV attracts carnivores and r_3 expresses attracted carnivores remove herbivores. r_4 expresses mutation of plants from honest to cry wolf plant and r_5 expresses the learning of carnivores; they learnt and avoid to be attracted by the HIPV so the population of carnivores go to the HIPV is decreased. r_6 and r_7 are natural death of dis-honest plants and carnivores.

3.1 Result of Simulation

We set the reaction constants, k_1 to k_7 as 0.9, 0.5, 0.5, 0.4, 0.5, 0.5, 0.5, respectively, τ = 0.6 and the quantity of honest signal is 30, the quantity of dis-honest signals and the number of carnivores are zero, in the initial state; this parameter setting indicates the growth of herbivore is high and the mutation rate from honest plant to wolf is small. Since the quantity of dis-honest signal is not too large, HIPV does not evolve (Figure 2). Next, we increase the quantity of dis-honest

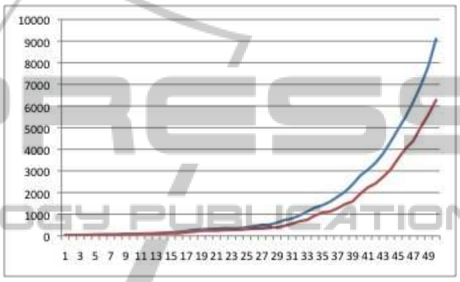

Figure 2: When the quantity of dis-honest signals are not too large, upper line indicates the quantity of honest signal and below, dis-honest signal; the vertical axis illustrates the quantity of HIPV (both honest and dis-honest signals) and the horizontal axis illustrates the steps. The biomass of plant is 10,000 so the plant biomass reaches to near zero

signals and retarded carnivores attractiveness to the HIPV, in order to realize it, we change the reaction constants for the rule of $w_i, c_i \to w_i(r_5)$. We set k_1 to k_7 as 0.9, 0.5, 0.5, 0.7, 0.5, 0.5, 0.5, respectively, τ = 0.6 and the quantity of honest signal is 30 and quantity of dis-honest signals and the number of carnivores are zero, in the initial state. In this case, HIPV evolved and various types of HIPV emerge (Figure 3).

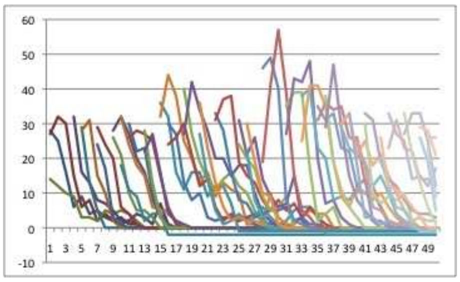

Figure 3: When the quantity of dis-honest signals are large, each lines indicates the quantity of honest and dis-honest signals; the horizontal axis illustrates the quantity of HIPV (both honest and dis-honest signals) and the horizontal axis illustrates the steps.

4 MODEL WITH GEOGRAPHIC SPACE

We model the system by using two dimensional Cellular Automaton (2DCA); the geographic space is square lattice and the eight cells surrounding a central cell (Moore neighbour); in the initial state, plants are distributed on the lattice; every plant grows in the same growth rate and when the its size (we call the size of a plant as "biomass" in the below) reaches the given value, stop growing and a new plant sprout in the neighbouring empty space.

In several randomly selected plants, herbivores come and start feeding; they increase the population by feeding and if the number of herbivores exceeds its biomass, the plant goes to die out and all herbivores move and distribute randomly to the nearest plants; plants start producing chemical signal when the population of herbivores exceeds the given threshold (honest plant). Each carnivores search the chemical signal by walking on the lattice, carnivores expense "physical power" by walking and if a carnivore finds the plant which has been suffered from feeding damage by herbivores (we call such a plant as "patch" in the below) , the carnivore removes all herbivores and gains its physical power according to the number of herbivores in the plant, while if a carnivore spends all physical power before finding the plant having feeding damage, it goes to die.

4.1 Cry Wolf Plant and Evolution of Signal

When a new plant sprouts, randomly selected plant become "cry wolf plant" and it generates chemical signal when it is suffered from small amount of feeding damage; in the initial state, there are no cry wolf plants and all plants and carnivores uses the same signal; however in the lapse of steps, the number of cry wolf plants increase and carnivores attract to such cry wolf plants. Each carnivore judges the quality of signal by "(the number of herbivores in the plant) / (the distance from the former patch) = Evaluation Value (EV)", if the EV is lower than given threshold, the carnivore judge and learn the plant as cry wolf and attractiveness of the signal becomes low. Hence as the population of cry wolf plants increases, the attractiveness of carnivores becomes low, so honest plants have to produce different HIPV. In ecological systems, different HIPVs are continuously generated by mutated plants (Shiojiri et al., 2010), if there are no cry wolf plants, carnivores do not learn other HIPV and plants producing different type HIPV can not attract carnivores and die out, however if the population of cry wolf plants increases, carnivores explore different HIPV randomly so such mutated plants can have the possibility to attract carnivores.

Learning of a Carnivore

In order to implement learning activity of a carnivore, we use the simple stochastic model, the polya's urn; this model is composed of a urn (pot) and balls, balls are painted with some sorts of colors. In this model, history of picking up a ball is remembered through following way; let us assume that there are three types (colors, red, black, white) of balls in a pot and the number of each colored balls are same (for simplicity, we assume that there are same number of each colored balls in the urn, here); when a "black" ball is picked up from the pot, $n, (n > 0)$ black balls are returned to the urn, hence the probability of selecting a black ball is increased, compared with other colors. We express the type of HIPV as the color of ball and the population of each HIPV as the number of balls. When a carnivore judges a HIPV as "honest signal" *n* balls of HIPV are added to its memory (urn) and if judges as "cry wolf", *m* balls of HIPV are removed from the memory and the *m* balls of "random walk" are added instead of them; when the carnivore select the ball of random walk, it explore nearest HIPV randomly.

5 RESULT OF SIMULATION

In the model with geological space, when the population of cry wolf plants increase, carnivores explore different type of HIPV and HIPV evolves (Figure.4). However, as the types of HIPV becomes larger, the

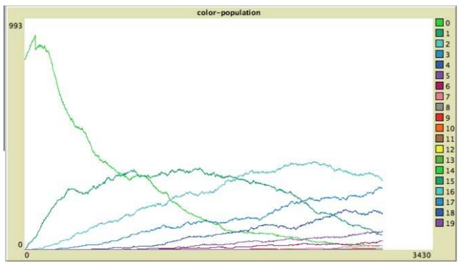

Figure 4: The time evolution of population of HIPV; each lines illustrates different HIPV.

number of plants producing each HIPV become relatively low; for example when there are 100 plants and produce two types of HIPV, if 50 plants produce the same HIPV, the probability of finding each of HIPV is 50/100, however if each of plant produces different HIPV, the probability of finding each of HIPV becomes 1/100; so as the types of HIPV increase, the most of carnivores expense all physical power before finding out the target HIPV producing plant and they go extinct. We confirmed this phenomenon in this model; this phenomenon is called the "Tower of Babel" and several theoretical contributions have been addressed it (Jansen and van Baalen, 2003). Hence, cry wolf plants may induce "Tower of Babel" effect, but we discover that when they form a "patch" in the geographic space, HIPV does not evolve and the Tower of Babel does not emerge (Figure5).

Food Court in an Ecological System

When cry wolf plants are sparsely distributed, carnivores may move long distance and meet a cry wolf plant, it expenses physical power largely but can not regain the power very much, because there are few herbivores and it does not enough for long traveled carnivore; However, if cry wolf plants form a patch, carnivores do not have to travel long distance and just hop around cry wolf plants and obtain herbivores; even if the population of herbivores in each plant is small, if it is a large patch, it will be able to offer enough herbivores to carnivores as a whole of the patch.

And honest plants do not produce HIPV soon, so carnivores have to wait until population of herbivores increases, but cry wolf plants produce HIPV soon and they can offer small amount of herbivores; so to speak, honest plants serve "full course meal" and cry wolf plants serve "light meal"; a patch of cry wolf plants is regarded as a "food court of light meals" hence carnivores do not judge the HIPV of cry wolf plants forming a patch as "honest signal" and HIPV does not evolve (Figure 5). In simulations, we use the same number of cry wolf plants and compare the case when they are distributed randomly with placed gathered; and confirm that in the former case, HIPV evolves and in the latter case, HIPV does not evolve.

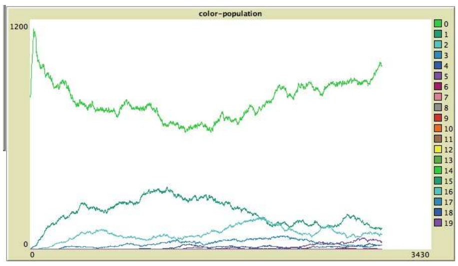

Figure 5: Time evolution of HIPV; each lines illustrates the different type of HIPV; there are several HIPVs in low concentration, they emerges by mutation of plants and changes of concentration are due to the growth and feeding damage by herbivores; even if such plant produces HIPV, carnivores do not learn other HIPV and they can not attract carnivores and die out

6 DISCUSSION

In order to consider the effect of geographic structure by using a model without using geographic structure, we consider a simple example. Let us consider a simple ARMS: the initial state is $\{a\}$ and it has a rule $R = \{a \to a, a\}$; if we consider this reaction by using the differential equation,

$$\frac{a}{dt} = a,$$

this is the Malthus equation and the number of a increases exponentially. However, in this ARMS the rule is applied sequentially (one rule is applied in the each step time), the time evolution of computation which starts from $\{a\}$ is;

$$\{a\} \to \{a,a\} \to \{a,a,a\} \to \dots,$$

hence the increment of the number of a is described as

$$M(a_i) = M(a_{i_1}) + 1,$$

where $M(a_i)$ denotes the multiplicity of a at step time of i; and the number of a increases lineally.

If the rule is applied in maximally parallel, the rule is applied as much as possible in the each step, the time evolution is $\{a\} \to \{a,a\} \to \{a,a,a,a\} \to\to \{a,a,a,a,a,a,a,a,a,a,a,a,a,a,a,a\} \to \dots,$ so the increment of the number of a is described as

$$M(a_i) = 2 \times M(a_{i-1}),$$

and the number of a increases exponential (non-linearly), $2^i, (i = 0, 1, 2, \dots,)$ and time evolution fits with the Malthus equation.

6.1 Linear, Non-linear and "Meso"-linear

In the ARMS with the maximally parallel rule application, reaction constants are defined for each reaction rule. For example, if we set the reaction constant for the rule $a \to a, a$ as 0.5, the expectation value of applying the rule is 0.5 $\times$ the size (cardinality) of the multiset; so the time evolution is, for example $\{a\} \to \{\mathbf{a}, \mathbf{a}\} \to \{a, a, \mathbf{a}, \mathbf{a}\} \to \{a, a, a, \mathbf{a}, \mathbf{a}, \mathbf{a}\} \to \{a, a, a, a, a, a, a, a, a,\} \dots$, where the rule is applied in parallel to bold characters. Hence the time evolution is neither linear nor non-linear. We name such dynamics as "meso"-linear, which means that the dynamics is in between linear and non-linear. In this example, when the reaction constant near to 1.0, its behavior resembles with the Malthus equation and near to 0.0, resembles linear system.

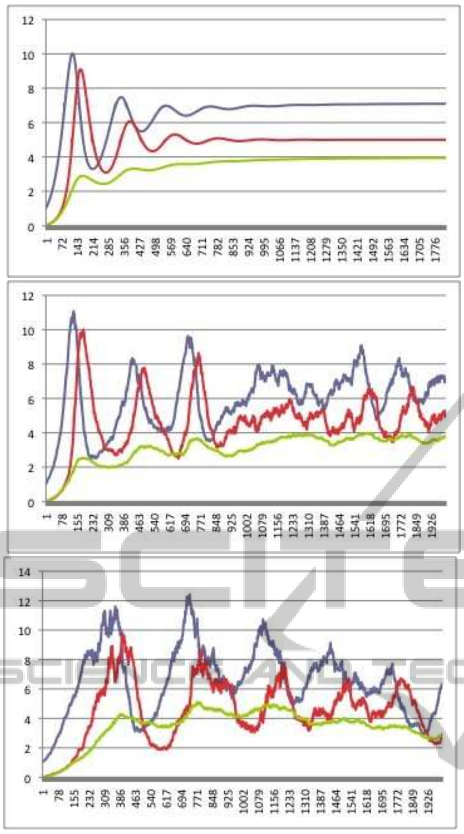

Figure 6: Simulation of the rate equation of the model of the Chemical Ecological system in the Section 3; the top is the same as Differential Eauation and from top to bottom, non-linearity becomes strong.

6.1.1 System Size and Meso-linearity

If the size of multiset and the reaction constant are small, the number of applicable rules is to be also few, on the other hand, if the size of multiset is large, even if the reaction constant is small, the number of applicable rules are not so few. In the ARMS with the rule of $a \to a, a$, the size of multiset in the initial state is more than 10, each of time evolution is not so different, however, when the size of multiset is 1 ($\{a\}$), its time evolution is different from others; we investigated the time evolution by changing the reaction constants as 1.0, 0.9, 0.8, ..., 0.1 and the size of multiset in the initial state as 10,000, 1,000, 100, 10, 1 and examine the meso-linearly compared with the reaction constant is 1.0 (maximally parallel);

We investigate the time evolution of the population of a in 10 steps from the initial state, the rule is applied in maximally parallel with reaction constants as 1.0, 0.9, 0.8, ... 0.1.

In each step, the difference between the population a with the reaction constant is 1.0 and others and the difference is divided by the size of multiset in the initial state for normalizing the value; so we confirm that when the size of multiset is 1, its time evolution is different from others. We transform the reaction rule of the model of chemical ecology (r_1 to r_7 in the Section 3) into the rate equation of chemical reactions and we confirmed that by inducing meso-linearlity, behavior of time evolutions becomes different (Figure6). Considering relation between meso-linearity and the effect of geological space is our future work.

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