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Development of an Intelligent Robot for an Agricultural Production Ecosystem (II) – Modeling of the Competition between Rice Plants and Weeds –

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Models of competition based on the Lotka–Volterra equation are introduced in this researching in order to develop an intelligent robot for a rice production ecosystem. These prediction equations are useful to estimate the competition between populations or biomasses of rice plants and weeds in different phases of the rice crop season and using this information about the superior plants, the robot will make decision about the appropriate timing for removing the snails in excess in paddy field; therefore snails remaining in the field can eat weed and rice plants will grow up with less competition.

INTRODUCTION

The development of a robot for an artificial ecosystem of agricultural production demands understanding and modeling an agricultural ecosystem. Damoto *et al.* (2003) reported the Lotka–Volterra equations for the competitive relation between crop and weeds. In this study, we will predict the populations of rice plants, and superior weeds (Tamagayatsuri (smallflower umbrella sedge), and Azena (smallflower umbrella sedge)) in paddy field by using models of interactions among three species on the agricultural ecosystem of the rice farming system in order to develop an intelligent robot which executes the tasks of control of weeds and snails in the paddy (Figure 1). Complex ecosystems with many species interacting with each other nonlinearly tend to exhibit chaotic dynamics (Keeling *et al.*, 2002; Tuda and Shimada, 2005; Vano, *et al.*, 2006).

SPECIES IN COMPETITION IN THE AGRICULTURAL PRODUCTION ECOSYSTEM

Two species in competition: rice plants and weed

The equations in our models for rice plants and weed are as follows

$$\frac{dN_1}{dt} = r_1 N_1 \left(1 - \frac{N_1 + \alpha_{12} N_2}{K_1}\right) \qquad (1)$$

$$\frac{dN_2}{dt} = r_2 N_2 \left(1 - \frac{N_2 + \alpha_{21} N_1}{K_2}\right) \qquad (2)$$

where, N_1: density or biomass of rice plants, N_2: density or biomass of weed, r_1: intrinsic rate of rice plants, r_2: intrinsic rate of weeds, α_{12}: weeds to rice plants competition coefficient, α_{21}: rice plants to weeds competition coefficient, K_1: rice plants capacity and K_2: weeds carrying capacity.

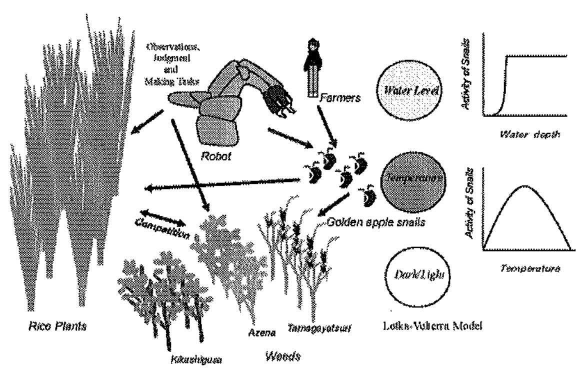

Fig. 1. Agricultural production ecosystem in paddy field.

To understand the competition dynamics ecologically we examine solutions at equilibrium analytically. The way to accomplish this is to set the two equations equal to zero and solve both for N_2 as a function of N_1 (Gotelli, 1998). The results are two equations for straight lines. These straight lines are called isoclines (Equations 3 and 4). An isocline represents combinations of N_1 and N_2 for which there is no net increase or decrease in population growth for each species (because dN/dt=0.) Where the lines cross, growth rates are zero for both species.

$$N_1 = K_1 - \alpha_{12} N_2 \qquad (3)$$

$$N_2 = K_2 - \alpha_{21} N_1 \qquad (4)$$

Case 1: The rice plants isocline is above the weed isocline. In the region below of both of isoclines, the populations and biomasses of weed and rice plants both increase. In the area of the chart between the two iso-

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clines, the population of weed isoclines decreases where as population of rice plants increases. The black circle at this point represents a stable equilibrium. The conclusion is that the population of weed declines to zero and rice plants increases to its carrying capacity (K_1). In this case rice plants have competitively excluded weed (Fig. 2a).

Case 2: Weed isocline is above rice plants isocline. In the region below of both of isoclines, the populations and biomasses of rice plants and weed both increase. In the area of the chart between the two isoclines, the populations and biomasses of rice plants decrease whereas the populations and biomasses of weed continue to increase. The result is that the populations and biomasses of rice plants decline to zero and weed increases to its carrying capacity (K_2). In this case the weed has competitively excluded the rice plants (Fig. 2b).

Case 3: The isoclines of the rice plant and weed cross one another. In this case the carrying capacity of rice plants (K_1) is higher than the carrying capacity of weed divided by the competition coefficient (K_2/α_{21}), and the carrying capacity of weed (K_2) is higher than the carrying capacity of rice plants divided by the competition coefficient (K_1/α_{12}). In the area below both rice plants and weed isoclines and above both rice plants and weed isoclines the populations and biomasses increase or decrease as in the first two cases, and there is an unstable equilibrium point where the rice plants and weed isoclines intersect. For the populations and biomasses above the weed isocline and below the rice plants isocline, the result becomes same as in the first case: competitive exclusion of weed by rice plants. In the area above the rice plants isocline and below the weed isocline, the result is the same as in the second case: competitive exclusion of rice plant by weed. The two stable equilibrium points are again represented by black circles. In this case, the result will depend on the initial populations or abundances of rice plants and weed (Fig. 2c).

Case 4: The isoclines cross one another, but in this case both rice plants and weed' carrying capacities are lower than the other's carrying capacity divided by the competition coefficient. Again, below both rice plants and weed isoclines the populations increase and above both rice plants and weed isoclines the populations decrease. In this case, however, when the populations and biomasses of the rice plants and weed are between the isoclines their vectors always head toward the intersection of the isoclines and two species are able to coexist at this stable equilibrium point. This is the result will not depend on the initial abundances (Fig. 2d).

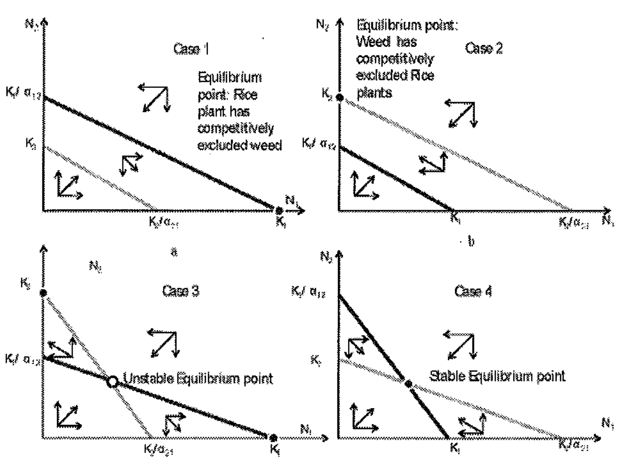

Fig. 2. State space graphs of the populations of rice plants and weed.

Jacobian Matrix for rice plants and weed

If $J(N_1, N_2)$ is a fixed point, we can use the equations 1 and 2 when growth rates are zero and then construct a Jacobian matrix.

$$\frac{dN_1}{dt}=r_1N_1\left(1-\frac{N_1+\alpha_{12}N_2}{K_1}\right)$$

$$0=r_1N_1-\frac{r_1N_1^2}{K_1}-\frac{\alpha_{12}r_1N_1N_2}{K_1} \tag{5}$$

$$\frac{dN_2}{dt}=r_2N_2\left(1-\frac{N_2+\alpha_{21}N_1}{K_2}\right)$$

$$0=r_2N_2-\frac{r_2N_2^2}{K_2}-\frac{\alpha_{21}r_2N_1N_2}{K_2} \tag{6}$$

Then we define the system of differential equations using the equations 5 and 6.

$$J(N_1,N_2)=\begin{bmatrix}\dfrac{\partial(Eq5)}{\partial N_1} & \dfrac{\partial(Eq5)}{\partial N_2}\\[2ex] \dfrac{\partial(Eq6)}{\partial N_1} & \dfrac{\partial(Eq6)}{\partial N_2}\end{bmatrix}$$

And we do linearization in order to find the Jacobian of the vector function of the nonlinear system. We get the rendered general Jacobian matrix for rice plants and weed in competition as follows,

$$J(N_1,N_2)=\begin{bmatrix} r_1-2\dfrac{r_1}{K_1}N_1-\dfrac{\alpha_{12}r_1}{K_1}N_2 & -\dfrac{\alpha_{12}r_1}{K_1}N_1\\[2ex] -\dfrac{\alpha_{21}r_2}{K_2}N_2 & r_2-2\dfrac{r_2}{K_2}N_2-\dfrac{\alpha_{21}r_2}{K_2}N_1\end{bmatrix} \tag{7}$$

Using the isoclines of the equations 3 and 4, we can know the general stationary point P_1 and P_2

$$P_1\,(K_1-\alpha_{12}N_2,\, K_2-\alpha_{21}N_1)$$

$$P_2\left(\frac{K_1-N_1}{\alpha_{12}},\ \frac{K_2-N_2}{\alpha_{21}}\right)$$

We could analyze the stability of the system by trough the evaluation of the Jacobian matrix in each fixed points and find the eigenvalues and eigenvectors. An eigenvalue of a square matrix is a scalar (λ) and the points attracted are negative eigenvalue and the points repelled are positive eigenvalues. An eigenvector is an axis of attraction. If the eigenvalues have negative real parts, the fixed point is asymptotically stable (attractor). If at least one eigenvalue has positive real part, the fixed point is unstable (repeller). If eigenvalues are pure imaginery, the fixed point could be stable or unstable.

Three species in competition: rice plants and weeds (Tamagayatsuri and Azena)

Lotka–Volterra–type competition models that involve three superior species (rice plants, Tamagayatsuri and Azena) will have the following equations:

Equation for population growth of rice plants.

$$\frac{dN_1}{dt} = r_1 N_1 \left(1 - \frac{N_1 + \alpha_{12} N_2 + \alpha_{13} N_3}{K_1}\right) \tag{8}$$

Equation for population growth of Tamagayatsuri.

$$\frac{dN_2}{dt} = r_2 N_2 \left(1 - \frac{N_2 + \alpha_{21} N_1 + \alpha_{23} N_3}{K_2}\right) \tag{9}$$

Equation for population growth of Azena.

$$\frac{dN_3}{dt} = r_3 N_3 \left(1 - \frac{N_3 + \alpha_{31} N_1 + \alpha_{32} N_2}{K_3}\right) \tag{10}$$

where N_1: density or biomass of rice plant biomass, N_2: density or biomass of Tamagayatsuri, N_3: density or biomass of Azena, r_1: intrinsic rate of rice plants, r_2: intrinsic rate of Tamagayatsuri, r_3: intrinsic rate of Azena, α_{12}: Tamagayatsuri to rice plants competition coefficient, α_{13}: Azena to rice plants competition coefficient, α_{21}: rice plants to Tamagayatsuri competition coefficient, α_{23}: Azena to Tamagayatsuri competition coefficient, α_{31}: rice plants to Azena competition coefficient, α_{32}: Tamagayatsuri to Azena competition coefficient, K_1: rice plants carrying capacity, K_2: Tamagayatsuri carrying capacity and K_3: Azena carrying capacity. The populations of the superior weeds, Tamagayatsuri and Azena were 750 and 496, respectively in a lot of 50 m^2 with a population of 750 rice plants and practicing organic agriculture in Kyushu University Farm on August of 1996 (Table 1). A chart with the three species (rice plants, Tamagayatsuri and Azena) in competition after transplanting on June 20th, 2006, in an area of 50 m^2 is presented in Fig. 3. In order to make the chart, we coded and run a program in Matlab and solved the ordinary differential equation system by the numerical method of Runge–Kutta. The data considered were: $r_1 = 0.15$, $r_2 = 0.20$, $r_3 = 0.15$, $\alpha_{12} = 0.06$, $\alpha_{13} = 0.08$, $\alpha_{21} = 0.06$, $\alpha_{23} = 0.07$, $\alpha_{31} = 0.08$, $\alpha_{32} = 0.07$, $K_1 = 750$, $K_2 = 500$ and $K_3 = 200$. The initial conditions for the three superior species in the agricultural production ecosystem were as follows $N_1 = 750$, $N_2 = 1$ and $N_3 = 1$. We can also see from the Fig. 3 that after 20 days after transplanting of rice seedlings, the populations of Azena and Tamagayatsuri and rice plants are increasing. In the case of rice plants there is minor error due we used Lotka–Volterra to model the competition among them. The population of rice plants should be almost constant over the crop season. The populations of the three species in the same plot on July 30th, 2006 (forty days after transplanting) were as follows, $N_1 = 742$, $N_2 = 476$ and $N_3 = 38$ and the populations of three superior species became stable after 60 days after transplanting.

The general isoclines for three species in competition are as follows.

Isocline 1.

$$N_1 = K_1 - \alpha_{12} N_2 - \alpha_{13} N_3 \tag{11}$$

Isocline 2.

$$N_2 = K_2 - \alpha_{21} N_1 - \alpha_{23} N_3 \tag{12}$$

Isocline 3.

$$N_3 = K_3 - \alpha_{31} N_1 - \alpha_{32} N_2 \tag{13}$$

Table 1. Results of researching on kind and population of superior weeds in lowland paddy field at Kyushu University farm on August 12th, 1996

Experiment Site	Tamagayatsuri	Azena
a. Organic Agriculture Without chemicals	496	38
b. Habitual Practice (Herbicide)	0	0

Tamagayatsuri: smallflower umbrella sedge (*Cyperus difformis* L.)
Azena: common false pimpernel (*Lindernia procumbens* (Krock.) Borbas → [Lindernia pyxidaria L.])
The weeds were researched on August 12th, 1996 in an experimental site of 50 square meters.

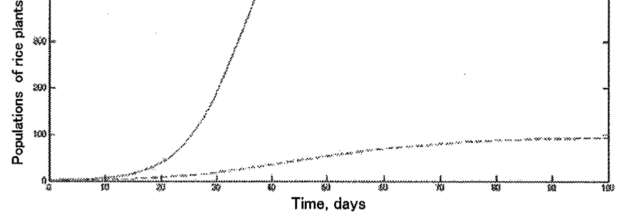

Fig. 3. Populations of three superior species in competition (rice plants, Tamagayatsuri and Azena) after transplanting of rice seedlings in a lot of 50 m^2 in Kyushu University Farm on June 20th, 2006.

The Fig. 4 shows us the three isoclines of the competition model among three superior species (rice plants, Tamagayatsuri and Azena). In Lotka–Volterra model the three species have same populations and coexist in an equilibrium point, P_e in natural ecosystems. However, in the agricultural production ecosystem of paddy, the period of the crop season is much shorter and farmers do several farm works such as: irrigation, remove of weeds and snails, so the P_e is not reached. The Fig. 5 shows the directions of vectors fields of the three species in the competition model in the agricultural production ecosystem of paddy. A phase portrait between rice plants and Tamagayatsuri is showed in the Fig. 6, whereas the Fig. 7 shows us a phase portrait among three species in competition (rice plants, Tamagayatsuri and Azena).

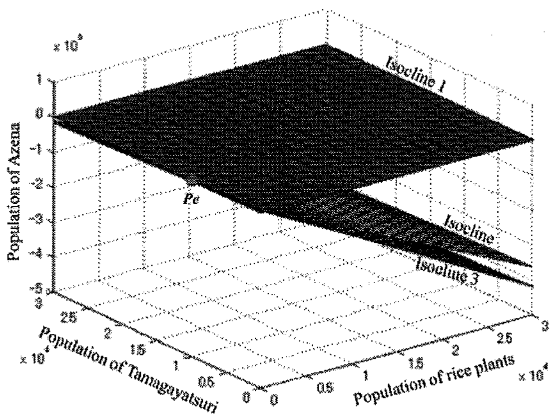

Fig. 4. Isoclines of the competition model between three species (rice plants, Tamagayatsuri and Azena).

Jacobian Matrix for rice plants, Tamagayatsuri and Azena

If $J(N_1, N_2, N_3)$ is a fixed point, we can use the equations 8, 9, and 10 when growth rates are zero and then construct a Jacobian matrix.

$$\frac{dN_1}{dt}=r_1N_1\left(1-\frac{N_1+\alpha_{12}N_2+\alpha_{13}N_3}{K_1}\right)$$

$$0=r_1N_1-\frac{r_1N_1^2}{K_1}-\frac{\alpha_{12}r_1N_1N_2}{K_1}-\frac{\alpha_{13}r_1N_1N_3}{K_1} \quad (14)$$

$$\frac{dN_2}{dt}=r_2N_2\left(1-\frac{N_2+\alpha_{21}N_1+\alpha_{23}N_3}{K_2}\right)$$

$$0=r_2N_2-\frac{r_2N_2^2}{K_2}-\frac{\alpha_{21}r_2N_1N_2}{K_2}-\frac{\alpha_{23}r_2N_2N_3}{K_2} \quad (15)$$

$$\frac{dN_3}{dt}=r_3N_3\left(1-\frac{N_3+\alpha_{31}N_1+\alpha_{32}N_2}{K_3}\right)$$

$$0=r_3N_3-\frac{r_3N_3^2}{K_3}-\frac{\alpha_{31}r_3N_1N_3}{K_3}-\frac{\alpha_{32}r_3N_2N_3}{K_3} \quad (16)$$

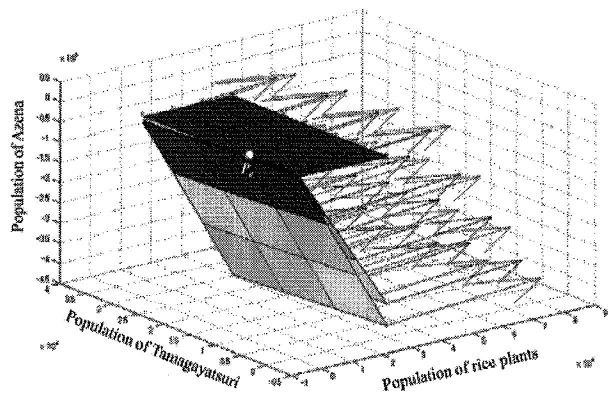

Fig. 5. Directions of vector fields of the three species (rice plants, Tamagayatsuri and Azena) in competition model in the agricultural production ecosystem of paddy.

Then we define the system of differential equations using the equations 14, 15 and 16.

$$J(N_1, N_2, N_3)=\begin{bmatrix} \frac{\partial(Eq14)}{\partial N_1} & \frac{\partial(Eq14)}{\partial N_2} & \frac{\partial(Eq14)}{\partial N_3} \\ \frac{\partial(Eq15)}{\partial N_1} & \frac{\partial(Eq15)}{\partial N_2} & \frac{\partial(Eq15)}{\partial N_3} \\ \frac{\partial(Eq16)}{\partial N_1} & \frac{\partial(Eq16)}{\partial N_2} & \frac{\partial(Eq16)}{\partial N_3} \end{bmatrix}$$

And we do linearization in order to find the Jacobian of the vector function of the nonlinear system. We get the rendered general Jacobian matrix for three species in competition as follows,

$$J(N_1, N_2, N_3)=\begin{bmatrix} a_{11} & -N_1\frac{\alpha_{12}r_1}{K_1}N_1 & -\frac{\alpha_{13}r_1}{K_1}N_1 \\ -\frac{\alpha_{12}r_2}{K_2}N_2 & b_{22} & -\frac{\alpha_{23}r_2}{K_2}N_2 \\ -\frac{\alpha_{31}r_3}{K_3}N_3 & -\frac{\alpha_{32}r_3}{K_3}N_3 & c_{33} \end{bmatrix} \quad (17)$$

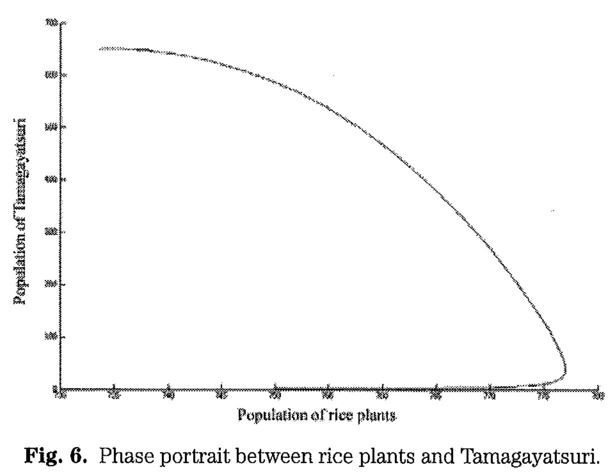

Fig. 6. Phase portrait between rice plants and Tamagayatsuri.

where

$$a_{11} = r_1 - 2\frac{r_1}{K_1}N_1 - \frac{\alpha_{12} r_1}{K_1}N_2 - \frac{\alpha_{13} r_1}{K_1}N_3$$

$$b_{22} = r_2 - 2\frac{r_2}{K_2}N_2 - \frac{\alpha_{21} r_2}{K_2}N_1 - \frac{\alpha_{23} r_2}{K_2}N_3$$

$$c_{33} = r_3 - 2\frac{r_3}{K_3}N_3 - \frac{\alpha_{31} r_3}{K_3}N_1 - \frac{\alpha_{32} r_3}{K_3}N_2$$

Using the isoclines of the equations 11, 12 and 13 we can make the general equation of the stationary points P_1, P_2 and P_3

$$P_1\,(K_1 - \alpha_{12}N_2 - \alpha_{13}N_3\,,\ K_2 - \alpha_{21}N_1 - \alpha_{23}N_3,\ -\alpha_{31}N_1 - \alpha_{32}N_2) \quad (18)$$

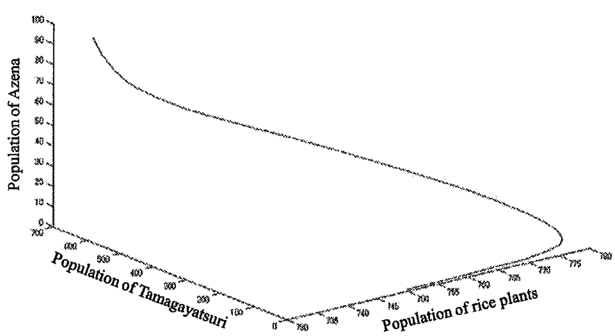

Fig. 7. Phase portrait between three species in competition (rice plants, Tamagayatsuri and Azena).

$$P_2\left(\frac{K_2 - N_2 - \alpha_{23}N_3}{\alpha_{21}},\ \frac{K_3 - N_3 - \alpha_{31}N_1}{\alpha_{32}},\ \frac{K_1 - N_1 - \alpha_{12}N_2}{\alpha_{12}}\right) \quad (19)$$

$$P_3\left(\frac{K_3 - N_3 - \alpha_{32}N_2}{\alpha_{31}},\ \frac{K_1 - N_1 - \alpha_{13}N_3}{\alpha_{12}},\ \frac{K_2 - N_2 - \alpha_{21}N_1}{\alpha_{23}}\right) \quad (20)$$

To analyze the stability of the agricultural production ecosystem, we should evaluate the Jacobian matrix for rice plants, Azena, and Tamagayatsuri in each fixed point and obtain the eigenvalues and eigenvectors. The following is the analysis of the agricultural production ecosystem considering the stationary point P_1 of the equation 18 and the Jacobian matrix of the equation 17

$$J(P_1) = \begin{bmatrix} a_{11} & -a_{12} & -a_{13} \\ -b_{12} & b_{22} & -b_{23} \\ -c_{31} & -c_{32} & c_{33} \end{bmatrix}$$

where

$$a_{11} = r_1 - 2\frac{r_1}{K_1}(K_1 - \alpha_{12}N_2 - \alpha_{13}N_3) - \frac{\alpha_{12}r_1}{K_1}(K_2 - \alpha_{21}N_1 - \alpha_{23}N_3) - \frac{\alpha_{13}r_1}{K_1}(K_3 - \alpha_{31}N_1 - \alpha_{32}N_2)$$

$$a_{12} = \frac{\alpha_{12}r_1}{K_1}(K_1 - \alpha_{12}N_2 - \alpha_{13}N_3)$$

$$a_{13} = \frac{\alpha_{13}r_1}{K_1}(K_1 - \alpha_{12}N_2 - \alpha_{13}N_3)$$

$$b_{21} = \frac{\alpha_{12}r_2}{K_1}(K_2 - \alpha_{21}N_1 - \alpha_{23}N_3)$$

$$b_{22} = r_2 - 2\frac{r_2}{K_2}(K_2 - \alpha_{21}N_1 - \alpha_{23}N_3) - \frac{\alpha_{21}r_2}{K_2}(K_1 - \alpha_{12}N_2 - \alpha_{13}N_3) - \frac{\alpha_{23}r_2}{K_2}(K_3 - \alpha_{31}N_1 - \alpha_{32}N_2)$$

$$b_{23} = \frac{\alpha_{23}r_2}{K_2}(K_3 - \alpha_{31}N_1 - \alpha_{32}N_2)$$

$$c_{31} = \frac{\alpha_{31}r_3}{K_3}(K_3 - \alpha_{31}N_1 - \alpha_{32}N_2)$$

$$c_{32} = \frac{\alpha_{32}r_3}{K_3}(K_3 - \alpha_{31}N_1 - \alpha_{32}N_2)$$

$$c_{33} = r_3 - 2\frac{r_3}{K_3}(K_3 - \alpha_{31}N_1 - \alpha_{32}N_2) - \frac{\alpha_{31}r_3}{K_3}(K_1 - \alpha_{12}N_2 - \alpha_{13}N_3) - \frac{\alpha_{32}r_3}{K_3}(K_2 - \alpha_{21}N_1 - \alpha_{23}N_3)$$

The characteristic equation is given by

$$\det([A] - \lambda[I]) = 0$$

If [A] is a nxn matrix, then [X] $\neq$ 0 is an eigenvector of [A] if [A][X] = λ[X] where λ is a scalar and [X] $\neq$ 0. The scalar λ is called the eigenvalue of [A] and [X] is called the eigenvector corresponding to the eigenvalue λ.

$$\det\begin{bmatrix} a_{11}-\lambda & -a_{12} & -a_{13} \\ -b_{12} & b_{22}-\lambda & -b_{23} \\ -c_{31} & -c_{32} & c_{33}-\lambda \end{bmatrix} = 0$$

$$\det = A + B + C = 0$$

$$A = -\lambda^3 + (a_{11} + b_{22} + c_{33})\lambda^2 - (a_{11}b_{22} + a_{11}c_{33} + b_{22}c_{33} - b_{23}c_{32})\lambda + a_{11}b_{22}c_{33} - a_{11}b_{23}c_{32}$$

$$B = a_{12}b_{12}\lambda - a_{12}b_{12}c_{33} - a_{12}b_{23}c_{31}$$

$$C = a_{13}c_{31}\lambda - a_{13}b_{12}c_{32} - a_{13}b_{22}c_{31}$$

$$C = a_{13}c_{31}\lambda - a_{13}b_{12}c_{32} - a_{13}b_{22}c_{31}$$

$$\det = -\lambda^3 + (k_1)\lambda^2 - (k_2)\lambda + k_3 = 0$$

where

$$k_1 = a_{11} + b_{22} + c_{33}$$

$$k_2 = a_{12}b_{12} + a_{11}b_{22} + a_{13}c_{31} + a_{11}c_{33} + b_{22}c_{33} - b_{23}c_{32}$$

$$k_3 = a_{11}b_{22}c_{33} - a_{11}b_{23}c_{32} - a_{12}b_{12}c_{33} - a_{12}b_{23}c_{31} - a_{13}b_{12}c_{32} - a_{13}b_{22}c_{31}$$

We get the following equation

$$-\lambda^3 + (k_1)\lambda^2 - (k_2)\lambda + k_3 = 0 \qquad (21)$$

The equation 21 has three cubic roots, which are the eigenvalues. If we also consider the following data: N_1= 742, N_2= 1, N_3= 1, r_1= 0.15, r_2= 0.2, r_3= 0.15, a_{12}= 0.06, a_{13}= 0.08, a_{21}= 0.06, a_{23}= 0.07, a_{31}= 0.08, a_{32}=0.07, K_1= 750, K_2= 500 and K_3= 200, we can get the Jacobian Matrix as follows,

$$J(P_1) = \begin{bmatrix} -2.85 & -0.009 & -0.012 \\ -0.00024 & 0.18 & -0.000028 \\ -0.00006 & -0.000052 & 0.089 \end{bmatrix}$$

We evaluated the Jacobian matrix in the point P_1 (750, 455, 141) and got the following eigenvalues: λ_1= –2.85, λ_2= 0.18 and λ_3= 0.89, therefore P_1 is unstable.

DISCUSSION

The farm works such as: tillage, paddling, transplanting and irrigations produce different initial conditions of the populations of rice plants and weeds such as Tamagayatsuri and Azena. The models, as an integral part of the development of an intelligent robot for an agricultural production ecosystem, estimate quantitatively the populations or biomasses of superior species over the time of the crop season. The prediction equations or models generated will be introduced into the memory of the agricultural production ecosystem robot in order to make decisions, in the different phases of the crop season, about the number of snails to be removed from paddy and we can change a harmful snail to a useful mollusk eating the weeds which are a constraint of both conservation agriculture production and the balance preservation of the rice agricultural ecosystem.

CONCLUSION

The stability of the competition among these three superior plants of rice production ecosystem is predicted by through of the eigenvalues of fixed points considering different farm works or phases of paddy. From our analysis of the competition among three superior plants (rice plants, Tamagayatsuri and Azena) without predation by golden apple snail, we can predict they coexist at a stable equilibrium point. It means the system is not chaotic but stable. The models generated will be introduced into the agricultural production ecosystem robot; therefore the robot can make decisions about the number of snails to remove from paddy. It is also necessary to consider factors, such as temperature, light and water depth dependency, which influences the snail's activity.

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Development of an Intelligent Robot for an Agricultural Production Ecosystem (III) – Modeling of the Predation of Rice Plants and Weeds by Golden Apple Snail –

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Models of the predation of rice plants and weeds by golden apple snails based on the Lotka– Volterra equations and the equations of Holling are introduced in this researching. These prediction equations are useful to estimate the number of snails in different phases of the rice crop season; however they should be modified to fit better to the rice production ecosystem and then this information will be used for the agricultural production robot in order to make decisions about the appropriate timing for removing the snails in excess in paddy field.

INTRODUCTION

In the ecosystem of the paddy, the golden apple snails are serious invaders in Asian paddy. The snails cause immediate damage to the young seedlings especially in conservation agriculture. In the Figure 1, the snails voraciously eat rice plants just transplanted at Kyushu University Farm. The farm work to remove snails is tedious and the hand picking of snails consumes more than two hours per 10 a (Kunimoto and Nishikawa, 2008). In this researching, the number of snails is predicted in different phases of the paddy field using the Lotka–Volterra and Holling equations in order to develop an intelligent robot which executes the tasks of controlling of weeds and snails in the paddy.

Fig. 1. Predation of rice plants immediately after transplanting in lowland paddy field at Kyushu University Farm on the night of June 20th, 2008.

PREDATION MODEL IN THE AGRICULTURAL PRODUCTION ECOSYSTEM

In natural ecosystems we can see the behavior of the snails and superior plants (weeds or rice plants) according to the Lotka–Volterra model (Lotka, 1925, Volterra, 1926) as shown in Figure 2. We used the Lotka–Volterra equations considering the different works in the paddy for the farmers to do over the season of the crop in order to predict the populations of snails or biomasses of rice plants and weeds. We should understand the farm works in the artificial ecosystem of the paddy and establish the initial conditions to model the ecosystem of the paddy.

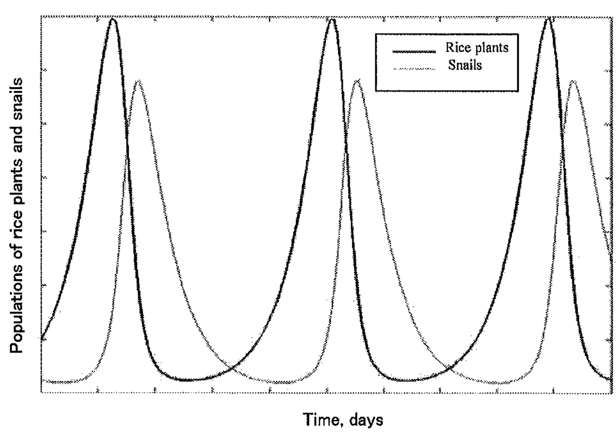

Fig. 2. Populations of plants and snails in a natural ecosystem based on Lotka–Volterra model.

Model for growth rate of plants and snails based on the equations of Lotka–Volterra

Our models are based on the equations of Lotka–Volterra are as follows

$$\frac{dN}{dt} = rN - aSN \quad (1)$$

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$$\frac{dS}{dt} = bSN - mS \tag{2}$$

Where, N: total density or biomass of superior plants (rice plants and weeds), S: density of snails, r: intrinsic rate for superior plants, $b = f \cdot a$: reproduction rate of snails per 1 plant eaten, f: the rate at which snails turn plants into offspring, a: predation rate coefficient, *i.e.*, is the search rate or attack efficiency of snails, m: snails mortality rate of snails.

To understand the predation dynamics ecologically we examine solutions at equilibrium analytically and get the isoclines as follows

$$N\,(r - aS) = 0 \tag{3}$$

$$S\,(bN - m) = 0 \tag{4}$$

Jacobian Matrix for snails and weeds

If $J(N, S)$ is a fixed point, we can use the equations 1 and 2 when growth rates are zero and then construct a Jacobian matrix.

$$\frac{dN}{dt} = rN - aSN$$

$$0 = rN - aSN \tag{5}$$

$$\frac{dS}{dt} = bSN - mS$$

$$0 = bSN - mS \tag{6}$$

Then we define the system of differential equations using the equations 5 and 6.

$$J(N,S) = \begin{bmatrix} \dfrac{\partial(Eq5)}{\partial N} & \dfrac{\partial(Eq5)}{\partial S} \\[2ex] \dfrac{\partial(Eq6)}{\partial N} & \dfrac{\partial(Eq6)}{\partial S} \end{bmatrix}$$

And we do linearization in order to find the Jacobian of the vector function of the nonlinear system. We get the rendered general Jacobian matrix for snail and rice plants in predation as follows,

$$J(N,S) = \begin{bmatrix} r - aS & -aN \\ bS & bN - m \end{bmatrix} \tag{7}$$

By using the equations 3 and 4, we have two solutions for the equation 3 as follows $N = 0$ or $S = r/a$. From the equation 4 we have the following roots: $S=0$ *and* $N=m/b$, so the equilibrium points are the following: $P_1(0,0)$ and $P_2(m/b, r/a)$

We analyzed the stability of the system by the evaluation of the Jacobian matrix in each fixed points, P_1 and P_2.

In P_1

$$J(0,0) = \begin{bmatrix} r - a \cdot 0 & -a \cdot 0 \\ b \cdot 0 & b \cdot 0 - m \end{bmatrix}$$

$$J(0,0) = \begin{bmatrix} r & 0 \\ 0 & -m \end{bmatrix}$$

The eigenvalues and eigenvectors in P_1 are as follow

$$\lambda_1 = r,\ \lambda_2 = -m,\ \xi_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix},\ \xi_2 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

In P_2

$$J(m/b,\ r/a) = \begin{bmatrix} r - a \cdot \dfrac{r}{a} & -a \cdot \dfrac{m}{b} \\[2ex] b \cdot \dfrac{r}{a} & b \cdot \dfrac{m}{b} - m \end{bmatrix}$$

$$J(m/b,\ r/a) = \begin{bmatrix} 0 & -\dfrac{am}{b} \\[2ex] \dfrac{br}{a} & 0 \end{bmatrix}$$

The eigenvalues and eigenvectors P_2 are as follows

$$\lambda_1 = r,\ \lambda_2 = -m,\ \xi_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix},\ \xi_2 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

or

$$\lambda = \pm\sqrt{a_1 b_1} \equiv \pm iw$$

Models for the populations of snails based on Lotka–Volterra equations in different phases of the agricultural production ecosystem of paddy in Kyushu University Farm

The main phases of the agricultural production of the paddy were described by Luna Maldonado and Nakaji (2008) and these are the models for those stages based on Lotka–Volterra equations for predation.

After tillage,

$$\frac{dS}{dt} = 0 \tag{8}$$

After rice paddling,

$$\frac{dS}{dt} = C \tag{9}$$

Where C: constant.

After transplanting,

$$\frac{dS}{dt} = bN_1S - mS \tag{10}$$

Where, S: density of snails, b: reproduction rate of snails, N_1: density of superior plants (rice plants and weeds), m: mortality rate of snails.

Ten days after transplanting,

$$\frac{dS}{dt} = bS(N_1 + N_2 + N_3) - mS \tag{11}$$

N_2: density of Tamagayatsuri, N_3: density of Azena,

After rice plants have reached 40 cm of height,

$$\frac{dS}{dt} = bS(N_2 + N_3) - mS \tag{12}$$

Model for growth rate of superior plants (rice plants and weeds) based on the equation of Holling

We can analyze what happens after transplanting of rice seedlings in the farm (Figure 3). We have in the rice field an initial amount of rice plants transplanted by the farmers. The snails, introduced by irrigation before paddling, start to eat the rice plants and the population of plants decreases where as the population of snails increase rapidly. After ten days the weeds will show up in the rice plot and the snails start to eat the weeds and the population of plants will keep almost constant. The snail's population still grows up until the populations of weeds start to decline, and then the snails suffered of hunger, therefore the population of snails will reduce, until the weeds will show up again in the field.

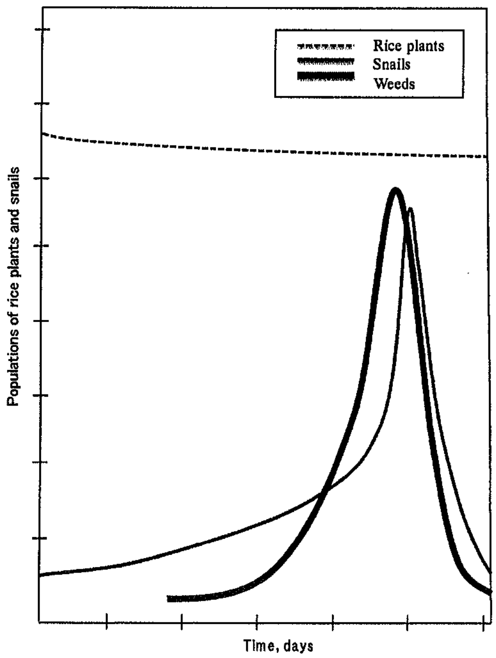

Fig. 3. Population dynamics of rice plants, snails and weeds in the agricultural production of paddy in lowland at Kyushu University Farm.

The Holling equation is an extension of the equation of Lotka–Volterra that adds a functional response (changes in the predation as prey's density increases). We considered the equations of Holling Type II (Holling, 1959) in order to fit our models to the agricultural production ecosystem as follows.

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) - \frac{pNS}{1+aN} \tag{13}$$

Where, r: intrinsic rate for superior plants (rice plants or weeds) in the paddy, N: total density or biomass of superior plants (rice plants and weeds), K: carrying capacity of superior plants, p: predation rate of superior plants by snails, S is the density of snails and a: predation rate coefficient, which is the search rate or attack efficiency of snails.

The equation 13 can be expressed as follows

$$\frac{dN}{dt} = -\frac{rN^2}{K} + rN - \frac{pNS}{1+aN}$$

Isocline

$$\frac{dN}{dt} = 0$$

$$0 = -\frac{rN^2}{K} + rN - \frac{pNS}{1+aN}$$

There are three possible equilibrium solutions for N as follows

$$N = 0 \tag{14}$$

or

$$N = \frac{a\left(rka - r \pm \sqrt{r^2k^2a^2+2r^2ka+r^2-4rapSk}\right)}{2r} \tag{15}$$

and

$$S = \frac{r}{p}\,(1+aN)\left(1+\frac{N}{K}\right) \tag{16}$$

Model for growth rate of snails based on the equation of Holling

$$\frac{dS}{dt} = \frac{bNS}{1+aN} - mS \tag{17}$$

Where, b: reproduction rate of snails and m: mortality rate of snails.

Isocline

$$\frac{dS}{dt} = 0$$

$$0 = \frac{bNS}{1+aN} - mS$$

The equilibrium solution is as follows

$$S = 0 \tag{18}$$

and

$$N = \frac{m}{b - ma} \tag{19}$$

Jacobian Matrix for snail and superior plants

If $J(N,S)$ is a fixed point, we can use the equations 13 and 17 when growth rates are zero and then construct a Jacobian matrix.

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) - \frac{pNS}{1+aN}$$

$$0 = -\frac{rN^2}{K} + rN - \frac{pNS}{1+aN} \tag{20}$$

$$\frac{dS}{dt} = \frac{pNS}{1+aN} - mS$$

$$0 = -\frac{pNS}{1+aN} - mS \tag{21}$$

Then we define the system of differential equations using the equations 20 and 21.

$$J(N,S) = \begin{bmatrix} \dfrac{\partial(Eq20)}{\partial N} & \dfrac{\partial(Eq20)}{\partial S} \\ \dfrac{\partial(Eq21)}{\partial N} & \dfrac{\partial(Eq21)}{\partial S} \end{bmatrix}$$

And we do linearization in order to find the Jacobian of the vector function of the nonlinear system. We get the rendered general Jacobian matrix for snails and superior plants as follows,

$$J(N,S) = \begin{bmatrix} -\dfrac{2rN}{K} + r - \dfrac{pS}{1+aN} + \dfrac{apNS}{(1+aN)^2} & -\dfrac{pN}{1+aN} \\ \dfrac{bS}{1+aN} - \dfrac{abNS}{(1+aN)^2} & \dfrac{bN}{1+aN} - m \end{bmatrix} \tag{22}$$

Models for the populations of snails based on Holling equations in different phases of the agricultural production ecosystem of paddy in Kyushu University Farm.

After tillage,

$$\frac{dS}{dt} = 0 \tag{23}$$

After rice paddling,

$$\frac{dS}{dt} = C \tag{24}$$

Where C: constant.

After transplanting,

$$\frac{dS}{dt} = \frac{bN_1S}{1+aN} - mS \tag{25}$$

Where, S: density of snails, b: reproduction rate of snails, N_1: density of rice plants and m: mortality rate of snails.

Ten days after transplanting,

$$\frac{dS}{dt} = \frac{b(N_1+N_2+N_3)S}{1+aN} - mS \tag{26}$$

N_2: density of Tamagayatsuri, N_3: density of Azena,

After rice plants have reached 40 cm of height,

$$\frac{dS}{dt} = \frac{b(N_2+N_3)S}{1+aN} - mS \tag{27}$$

After transplanting, the initial conditions were N=742, S=100, r=1, K=750, p= 0.002, a=0.1, b=0.012 and m=0.1 we can get the chart of the Figure 4 using the equation of Holling. In this phase of the rice crop season the weeds have not shown up in the agricultural production ecosystem. The snails start to eat young rice plants. We can also see from the Figure 4 that population of rice plants increased a little bit from 742 to 760 according to

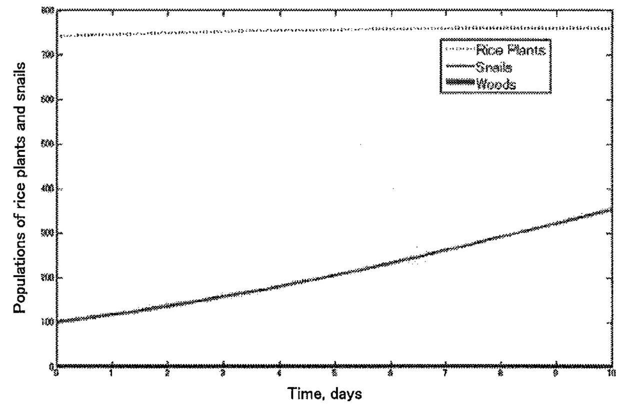

Fig. 4. Population dynamics of snails, rice plants and none weeds during day 1 to day 10 after transplanting in a lot of 50 square meters.

the model used for ten days after transplanting.

We obtained the chart of the Figure 5 considering from day 10 to day 100 after transplanting. The initial conditions were N=760, S=353, W=1 r=1, K=750, p=0.002, a=0.1, b=0.012 and m=0.1. Where W: population of weeds. In this phase of the rice crop season the weeds have shown up in the agricultural production ecosystem and snails eat both rice plants and weeds.

Using the equations 14, 15, 16, 19 and 20, we can obtain the general equations of the stationary points by substitution of the N and S in the general Jacobian equation 23 and then get the eigenvalues.

We analyzed the populations of plants and snails in one of the fixed points by using Holling equations and found that N=50 and S=400, and the Jacobian matrix is as follows,

$$J(P_1) = \begin{bmatrix} 1.642 & -0.019 \\ 0.0002 & 0.018 \end{bmatrix}$$

The eigenvalues are: λ_1=1.640, λ_2=0.018, therefore that point is unstable.

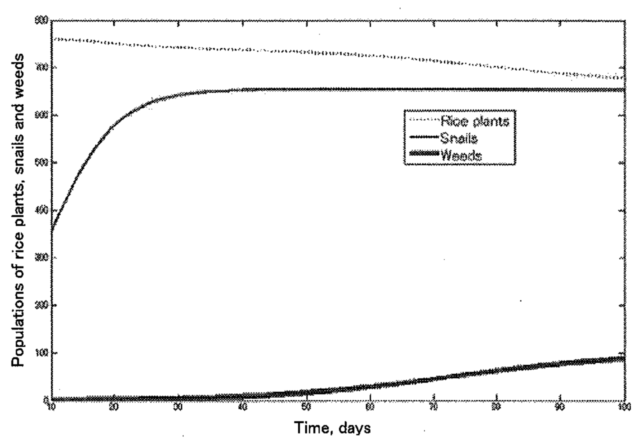

Fig. 5. Population dynamics of snails, rice plants and weeds from day 10 to day 100 after transplanting in a lot of 50 square meters.

DISCUSSION

The Lotka–Volterra and Holling equations estimate quantitatively the populations of snails and plants; however, we should consider the different stages over the crop season and make models that fit to those phases of the ecosystem of rice production. Using the equations of Holling we found that the first ten days after transplanting, the population of rice plants increased a little bit and then became stable, however in the ecosystem of paddy, the snails consume rice plants and therefore the density of rice plants should be decreased and then becomes stable.

In analysis of one the fixed points, N=50 and S=400; however in the agricultural production ecosystem they should be about N=730 and S=2.

CONCLUSION

The biodiversity of the agricultural production ecosystem will be enriched by through the prediction of the number of snails to be removed of paddy in the different phases of crop season. The models based on the equations of Lotka–Volterra and Holling considered the different farm works; however those models should be modified in order to fit better to the ecosystem of rice production. It is also necessary to model the agricultural production ecosystem considering factors, such as temperature, light and water depth.

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