Modeling the Area Restrict Searching strategy of stingless bees, *Trigona biroi*, as a Quasi-Random Walk process

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ABSTRACT

Area Restrict Searching strategy is one of the techniques used by stingless bees, *Trigona biroi*, in foraging patchily distributed food sources. In this search technique, bees increase the frequency of their flight turns especially when they just had encountered a rich food source. This search technique decreases the probability that the bees will miss high quality food sources, and increases the chance of finding richer feeding site. Bees tend to use this search technique because of the reality that food sources can deplete; and hence, they need to choose another feeding site which is usually the nearest similar neighbor. Moreover, an integral ingredient of the Area Restrict Searching strategy is the concept that bee species follow the Optimal Foraging Theory, i.e. they choose food sources based on some criteria that will maximize the benefits while maintaining cost-efficiency.

Various computational tools such as Monte Carlo Simulation and Biroi Preference Algorithm were employed in designing the stochastic model for mimicking the Area Restrict Searching strategy. A simplified version of the model is visualized using Netlogo, which is a multi-agent-based software. Examining the foraging patterns of bees will add knowledge into the study of pollination, which is helpful in increasing the production yield of flowering crops and in sustaining the natural conservation of plant biodiversity.

Keywords: random foraging behavior, Area Restrict Searching, *Trigona biroi*, Biroi Preference Algorithm

INTRODUCTION

Pollination is a vital process during the reproduction of plant species. Pollination management helps agriculturists in providing adequate food supply for human, and it helps environmentalists in sustaining the biodiversity of plants. Pollination can increase fruit production by almost 40% (Cervancia, et al., 2008). However, natural pollination has been neglected by humans, as men endeavor to use more and more fertilizers, pesticides and other artificial techniques to increase the yield of crops. In this study, the focus is not on artificial pollination but on natural pollination.

Insects like bees are good cross-pollinators, and they really have good role in plant reproduction. The famous words of Albert Einstein articulated the importance of bees:

"If the bees disappeared off the surface of the globe,
then man would only have four years of life left.
No more bees, no more pollination,
no more plants, no more animals, no more man"

In fact, it is estimated that approximately one-third of food supply is either directly or indirectly dependent on animal-pollinated plants such as bees (Kearns, et al., 1998).

There are factors that help determine the effectiveness of bees in pollination – the working habit of bees, the influence of environmental factors such as weather, the distribution of food patches, and the bee-behavior in food collection. Examining the behavior of bees in food collection will definitely add knowledge into the study of natural pollination. This study focuses on *Trigona biroi* Friese species from the tribe Meliponini (stingless bees), because they are common and native in the Philippines, and they are better pollinators than the Apis (honeybees) (Baconawa, n.d.).

Figure1. *Trigona biroi* or "Lukot"

Review of Related Literature

There are many studies about the foraging behavior of bees, in general. The most famous of these studies is the discovery that bees use round dance and waggle dance in communicating food location (Frisch, 1967). *Trigona carbonaria* commonly choose a feeding site with the closer distance to the hive (Nieh et al., 2000). Some bees prefer certain levels of sucrose concentration of nectars (Roubik et al., 1995; Scheiner et al., 2004; Schmidt et al., 2006); and some prefer only few groups of flower species (Ramalho, 1989).

Honeybees, *Apis mellifera* L, choose and discriminate natural odors, such as floral scents (Masson et al., 1993). Several studies showed that in different bee species, foragers deposit olfactory cues near the food sources to communicate their food preference, and these cues attract other foragers (Villa & Weiss, 1990; Aguilar & Sommeijer, 2001; Schmidt et al., 2003; Hrncir et al., 2004; Schmidt et al., 2005; Boogert et al., 2006; Witjes & Eltz, 2007; Contrera & Nieh, 2007). The presence of nestmates in a feeding site attracts foragers (Sánchez et al., 2008), and this occurrence affects choice of feeding site.

Sound signals from the scouts give information about the distance and sucrose concentration of the food sources (Aguilar & Briceño, 2002). Honeybees also choose food sources based on visuals, such as colors (Backhaus, 1993). Honeybees have the capacity to learn by association; and they can learn the colors, odors, shapes and structures of food sources

(Scheiner et. al, 2004). Bumblebees have the capacity to distinguish patterns based on experiences or memory (Seguin & Plowright, 2008).

Studies show that some flight behaviors of insects are random walk processes, and the famous flight strategy is the Lévy-loop flight (Reynolds, et al., 2007). Another strategy, the "near-far" foraging search suggests that bees look for food near the neighborhood of the last visited inflorescence as long as the foraging benefit is satisfactory, or else foragers will go far (Motro & Schmida, 1995). Bees have sophisticated flying aerodynamics, and their vision is very specialized. Their eyes are sensitive to ultra-violet and polarized light (Chittka & Dornhaus, 1999). The flight patterns of bees are evolutionary to achieve optimal foraging.

MODEL FORMULATION

The study aims to model the path of patch hopping of foragers, which closely follows a probabilistic pattern. The path is determined by statistically comparing the medians (or skewness) of the distribution of time visitation of bees in each food source. Assuming that the food sources are depleting, the combinatorial number of paths to take is going larger and larger as the number of food sources or feeders increases. The number of paths *P* that the bees can take from the beehive to feeder *S* can be computed as follows:

$$P_S=1+(n-1)+(n-1)(n-2)+(n-1)(n-2)(n-3)+\dots+(n-1)(n-2)\dots(n-(n-1))$$

where n is the total number of feeders

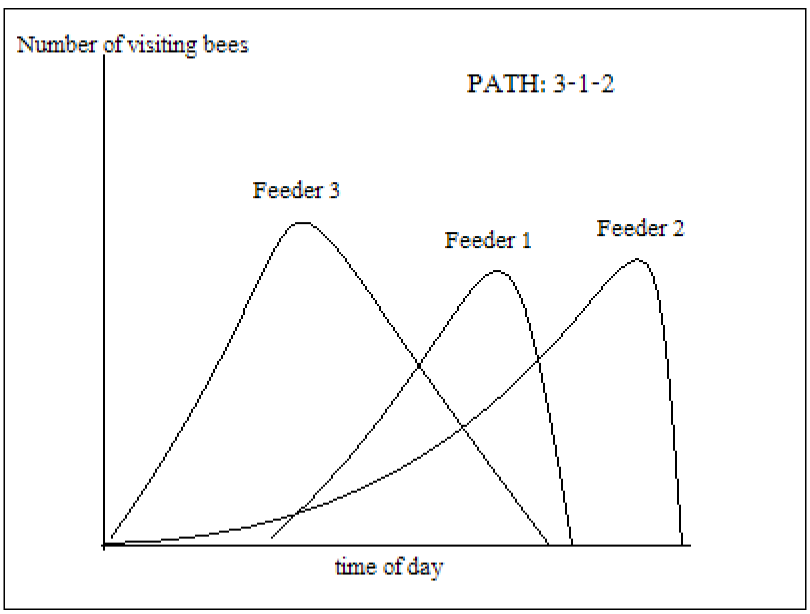

Figure 2. Method of determining the paths

Theoretically, the probability of going to a certain feeder is the average of all the probabilities of the possible paths. The probability that a path will be chosen is the product of all the probabilities of feeder-lines in the path. A feeder-line is defined as the path segment connecting a feeder to another feeder. In Figure 3, the number of paths that the bees can take from the beehive to *feeder S* is P_S = *1,951*, and the probability of going to *feeder S* using *path 1* is *C1xC2x…xC7*.

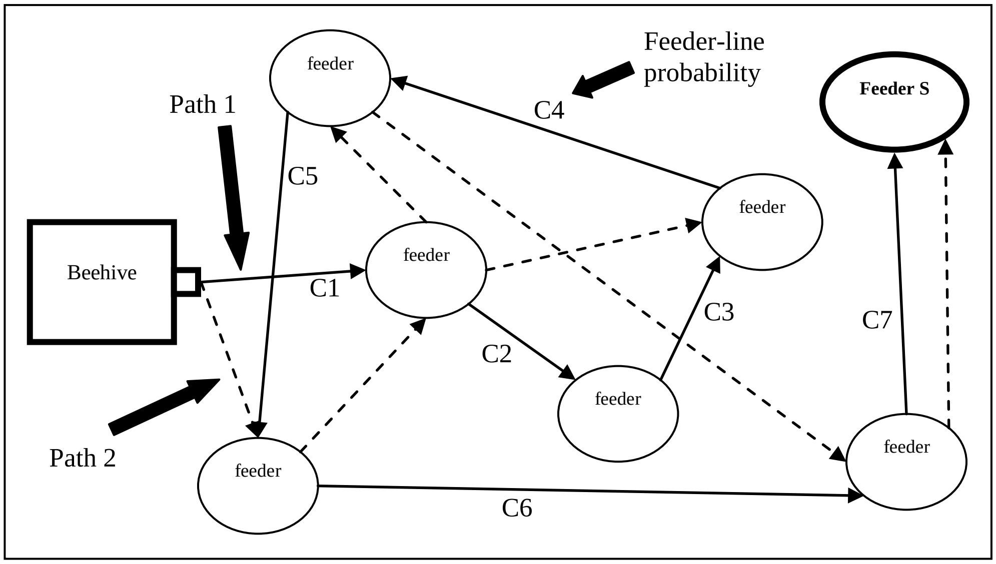

Figure 3. Sample paths of bee foraging

A stochastic process is a collection of random variables, e.g. the series of choosing and transferring to a new feeder. A random walk process S_n is a discrete Brownian Motion, and $S_n = S_0 + E_1 + E_2 + \ldots + E_n$, where the E_i's are independent and identically distributed random variables. The model is a quasi-random walk since the behavior of bees looks like random but is not purely random. The chances of going to certain food sources are not all equal, and the food-search follows certain pattern. The random like behavior is observable probably because of Lévy flights. However, the behavior of bees is affected by some recognized preferences and patterns, such as choice of nearest food location.

Nonetheless, using the theoretical way in studying the foraging behavior of bees by exhaustive enumeration is computationally costly as the number of feeders increases, and as probabilities become complicated. Simulation will make the model more tangible and easier to implement. Aside from the theoretical model, Monte Carlo Simulation with the Biroi Preference Algorithm was employed in designing the stochastic model for mimicking Area Restrict Searching strategy. Area Restrict Searching strategy is one of the foraging techniques of bees when feeding on patchily distributed resources. In this technique, bees try to exhaust possible food sources in an area before transferring to another area, to optimize energetics.

The Biroi Preference Algorithm is named after the inspiration from the stingless bees, *Trigona biroi*. The Biroi Preference Algorithm is authored by Figueroa, et al. (2009). The feeder-line probabilities are computed using the technique from the Biroi Preference Algorithm.

The Biroi Preference Algorithm assumes that bees follow the Optimal Foraging Theory (OFT), Ideal Free Distribution (IFD) and the Marginal Value Theorem (MVT). Following the OFT means that bees are maximizing the benefits that can be obtained from the food vis-á-vis the costs needed in foraging. Benefits may include calories that can be acquired and taste of the food; while costs may include time needed in foraging, distance and height to be traveled, and competitors present near the food. In IFD, the number of bees foraging a food source should be proportional to the amount of the food and to the area of the feeding site at a certain time. In MVT, bees find another food source when the profitability of the food is diminishing or when the amount of food is depleting. A bee colony builds a list of food sources using the information communicated by the scouts; and from this list, the foragers will know the profitability of each food source. However, apart from the scout-communicated information, individual foragers can search for food on their own. Moreover, the probabilities may change based on the current location of bees, which makes the process a Markov process with memory (Markov Chain of order m).

Bees do not forage from food source to food source on a straight direction, but they turn (Collevatti, et al., 2000). In Area Restrict Searching strategy bees increase the frequency of their flight turns especially when they just had encountered a rich food source. This search technique decreases the probability that the bees will miss high quality food sources, and increases the chance of finding richer feeding site. Bees tend to use this search technique because of the reality that food sources can deplete; and hence, they need to choose another feeding site which is usually the nearest similar neighbor. A simplified version of the model is visualized using Netlogo (Wilensky, 1999), which is a multi-agent-based software.

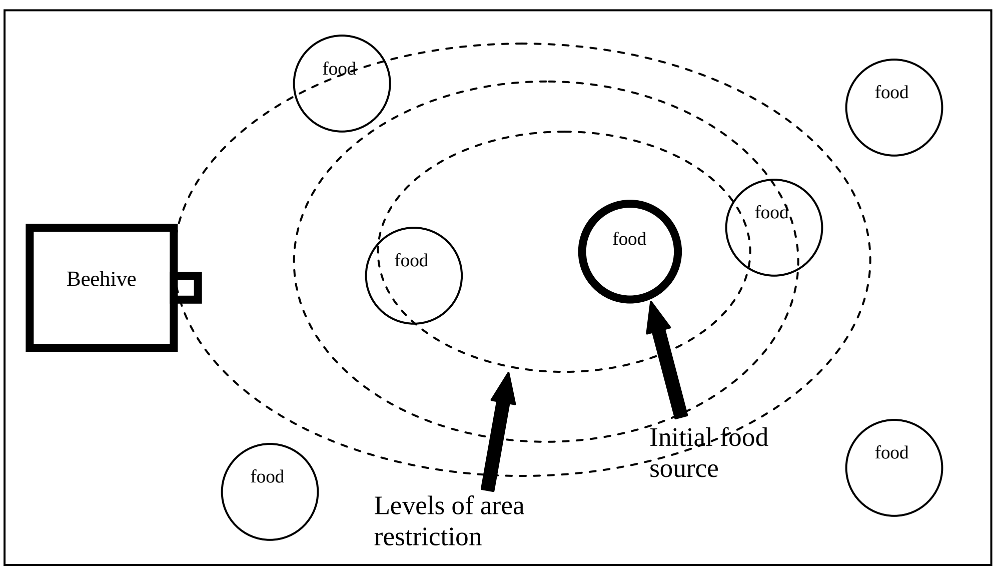

Figure 4. Area Restricted Searching – bees choose the next feeder which is near the old feeder and near the beehive.

Comparison of criteria for input in the Biroi Preference Algorithm can be done through field or laboratory experiments. For example, choice of food location based on sucrose concentration and distance of food location from the hive as criteria can be evaluated.

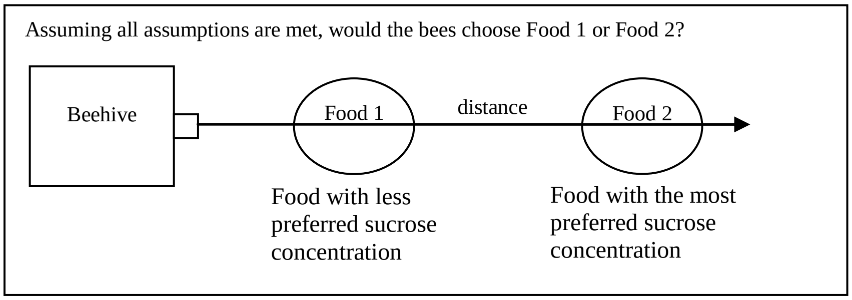

Figure 5. Sample Experimental Design in Comparing Criteria for the Biroi Preference Algorithm

THE BIROI PREFERENCE ALGORITHM

The following pseudo-code shows the generic steps of the algorithm.

Algorithm 1 ***Procedure*** *Biroi Preference Algorithm*

Setup *bee hive and **n** food sources.*

Input $C_1, C_2, ..., C_m$ (%criteria to be considered)

Input $A_{i,j}$ *where* $i=1,2,...,n$; $j=1,2,...,m$ (%values of each criteria per food source; $A_{i,j}$ is a positive real number, with usual notion of ordering)

Compute $W_1, W_2, ..., W_m$ *using Analytic Hierarchy Process* (%AHP can be fuzzy)

Do until $j=m$

$$Sum_j = \sum_{i=1}^{n} A_{i,j}$$

end do

Do until $i=n$

Do until $j=m$

$$Norm_{i,j} = \frac{A_{i,j}}{Sum_j}$$

end do

$$Weight_i = \sum_{j=1}^{m} \left(Norm_{i,j} \times W_j\right)$$

end do

Do until $i=n$

$$Probability_i = \frac{Weight_i}{\sum_{d=1}^{n} Weight_d}$$

end do

Assign $Probability_i$ *to food source **i**.*

Foragers randomly choose among the food sources based on the probabilities (%Example: If there are two food sources, say F_1 and F_2; and F_1 has $Probability_1=0.34$ and F_2 has $Probability_2=0.66$, then random numbers $\boldsymbol{s}$ will be assigned to F_1 where $0<\boldsymbol{s}<=34$, and random numbers $\boldsymbol{t}$ will be assigned to F_2 where $34<\boldsymbol{t}\leq 100$)

Do *the Simulation.*

Compute $B_1, B_2, ..., B_n$ (%number of bees in each food source per simulation tick)

Determine $E_1, E_2, ..., E_n$ *amounts of food source 1, 2, ..., n, respectively; and* $F_1, F_2, ..., F_n$ *areas of food source 1, 2, ..., n, respectively* (%per simulation tick)

If $\frac{B_i}{E_i} > constant_1$ *or* $\frac{B_i}{F_i} > constant_2$, ***then*** *do not allow new foragers to forage at food source* ***i****,*

and decrease number of bees to attain $\frac{B_i}{E_i} \leq constant_1$ *or* $\frac{B_i}{F_i} \leq constant_2$, *for i=1,2,...,n*

(%E_i's deplete as B_i's increase; food replenishment is optional)

The non-accepted or subtracted foragers transfer to other food source (%IFD and MVT assumption)

end if

end

Analytic Hierarchy Process (AHP) assumes that preferences of the bees are deterministic or certain. AHP also assumes that bees are rational in selecting the best of the food sources, which is the idea of OFT. The values needed in AHP can be derived using the results from field or laboratory experiments. The following steps show how to compute W_1, W_2, ..., W_m using AHP (Taha, 2003).

Algorithm 2 ***Procedure*** *AHP*

Rank the criteria C_1, C_2, ..., C_m *by comparing each of the criteria in an m x m Pairwise Comparison Matrix.*

The elements $q_{a,b}$*, for a=1,2,...,m and b=1,2,...,m, represent the relative ranking of criterion* ***a*** *and criterion* ***b****.*

Comparison factors should be discrete from 1 to 9.

$q_{a,b}$*=1 means criteria* ***a*** *and* ***b*** *are equally preferred.*

$q_{a,b}$*=5 means criterion* ***a*** *is strongly more preferred than criterion* ***b****.*

$q_{a,b}$*=9 means criterion* ***a*** *is extremely more preferred than criterion* ***b****.*

Other intermediate values between 1 to 9 are interpreted correspondingly.

If $q_{a,b}=k$, ***then*** $q_{b,a}=1/k$

If *a=b* ***then*** $q_{a,b}=1$.

The Pairwise Comparison Matrix:

$$Mat_o = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \cdots & C_m \end{array} \\ \begin{bmatrix} q_{1,1} & q_{1,2} & \cdots & q_{1,m} \\ q_{2,1} & q_{2,2} & \cdots & q_{2,m} \\ \vdots & \vdots & & \vdots \\ q_{m,1} & q_{m,2} & \cdots & q_{m,m} \end{bmatrix} \end{array}$$

Normalize the Pairwise Comparison Matrix.

$CSum_b = \sum_{a=1}^{m} q_{a,b}$ *for b=1,2,...,m* (%sum of column elements)

Do until *a=m*

Do until *b=m*

$newq_{a,b} = \frac{q_{a,b}}{CSum_b}$ (%normalized $q_{a,b}$'s)

end do

$W_a = \frac{\sum_{b=1}^{m} newq_{a,b}}{m}$ (%average of $newq_{a,b}$'s per row)

end do

$$Vectorw = \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_m \end{bmatrix}$$

Check for consistency (%optional)

Mat_o x Vectorw = *H*

$$H = \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_m \end{bmatrix} \text{ (\%assumed notation)}$$

$$Nmax = \sum_{a=1}^{m} h_a$$

$$ConsistencyIndex = \frac{(Nmax - m)}{m-1}$$

$$RandomConsistency = \frac{1.98 \times (m-2)}{m}$$

$$ConsistencyRatio = \frac{ConsistencyIndex}{RandomConsistency}$$

If *ConsistencyRatio ≥ 0.1,* ***then*** *the Pairwise Comparison Matrix has a high level of inconsistency*

end if

end

Figure 6 shows a screenshot of the simulation that was implemented in Netlogo. Netlogo is a cross-platform environment for developing models of complex systems using the multi-agent systems paradigm (Wilensky, 1999). The simulation shows two types of bees – the scouts (labeled with **S**) and the foragers (labeled with **F**). Scouts randomly search for food sources while foragers are programmed to simulate the Biroi Preference Algorithm.

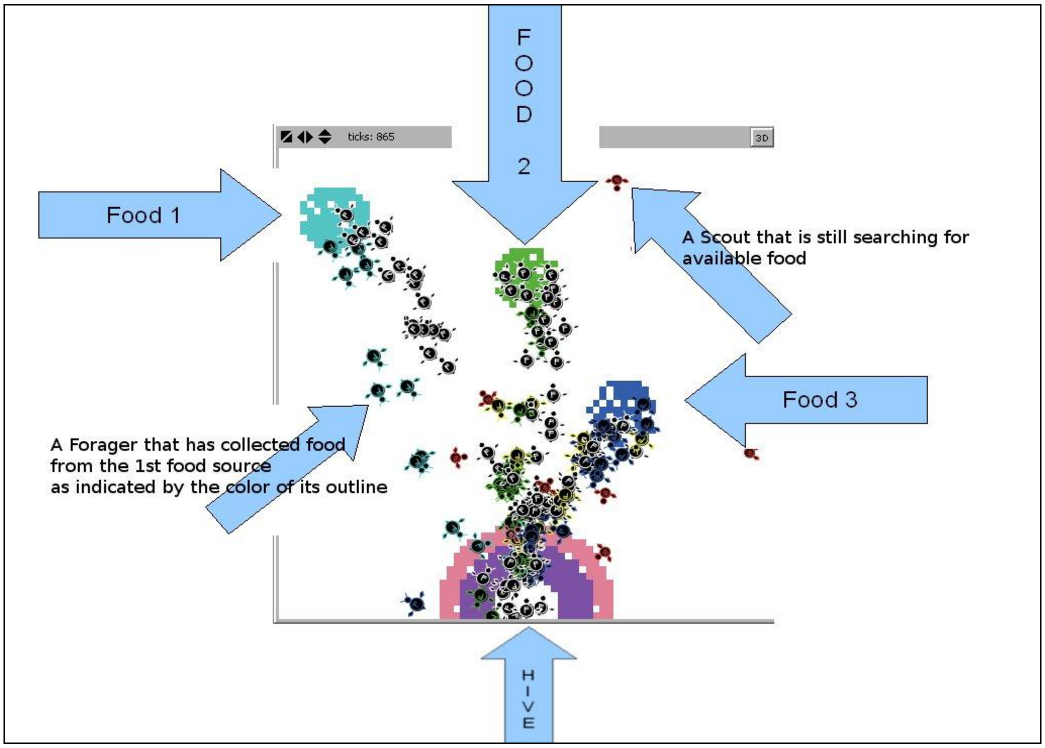

Figure 6: The Netlogo Simulation Panel

CONCLUDING REMARKS

It is usually difficult to study the behavior of complex systems, such as bee colonies; but it is still possible to approximate their behavior using simulation. Simulation of bee foraging behavior helps academicians in teaching ecological principles. It also helps beekeepers in visualizing the possible behavior of individual bees and the colonies.

Examining the foraging patterns of bees will add knowledge into the study of pollination, which is helpful in increasing the production yield of flowering crops and in sustaining the natural conservation of plant biodiversity. Flight and food search patterns, e.g. Area Restrict Searching strategy, of bees will help human predict the future behavior of bees as pollinators.

The foraging algorithms for bees can be used for modeling human behavior, such as the behavior of customers during queues. The applications of the algorithms are not confined with Ecology, and it can benefit other fields such as Operations Research, Business Management, Computer Science and Social Psychology.

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