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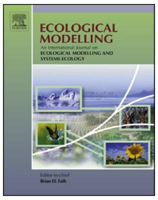

Friction based social force model for social foraging of sheep flock

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ABSTRACT

Social foraging of large herbivores shows collective behaviors of movement and grazing. Conspecific effects and interactions between individual and food distribution are known as important factors to influence foraging behaviors of sheep. Many rules of movement have been designed largely depending on conspecific effects. However, few simulation methods consider individual interactions with food distribution. In this paper, we first introduce instinct of feeding to represent individual interaction with currently located patch and then propose a novel friction based social force model to simulate different behaviors in social foraging. Friction force quantifies individual instinct of feeding on currently located patch since conspecific effects and attractions of food in other patches are external forces causing positional adjustment. In our model, agent decides to move if external forces are larger than current friction force and the destination patch can provide enough friction force to resist external forces. This result shows variable effects of instinct of feeding on social foraging and exhibits typical tortuous migration paths and departure-following collective movement of sheep flock. Our model emphasizes the importance of individual interactions with food distribution and may provide new insights into the mechanism governing internal decision process.

1. Introduction

During social foraging, large mammalian herbivores show collective movements, dynamic spatial patterns and grazing behaviors. Conspecific effects represent the actions and interactions of individuals which are essential factors inducing collective behaviors (Couzin and Krause, 2003). Many real field data have reported complex behaviors during social foraging caused by the interactions between animals and food distribution (Adler et al., 2001; de Knegt et al., 2007; Dumont and Hill, 2004). For example, movement of bighorn sheep always involves feeding behaviors which cause low migration speeds, winding trails and short movement distances (Woolf et al., 1970). Furthermore, de Knegt et al. (2007) found that goats (*Capra hircus*) could modulate speeds and tortuosity of movement paths according to different patch densities. Different from these wild herbivores, sheep (*Ovis aries*) keeps most of time stationary to feed in grazing case (Pillot et al., 2010). Meanwhile, a motivational conflict between conspecific effects and attraction of food appears: sheep may feed on less-preferred patches (Dumont and Boissy, 2000; Sibbald and Hooper, 2004) in order to stay close to other flock members when food is distributed unequally in discrete patches, but some "bold" sheep may move to new patches ignoring other flock members (Michelena et al., 2009). The motivational conflict indicates the largely unknown mechanism governing individual decision process which is a central issue to the study of collective behaviors (Conradt and List, 2009). Simulation model is a powerful method of visualizing the dynamic real world phenomena and helps to reveal the internal mechanisms if simulation results accord with real field data (Baumont et al., 2004; Parsons et al., 1994; Vicsek and Zafeiris, 2012). However, many related works such as consensus decision model and self-propelled model nearly overlook individual interactions with food distribution.

In consensus decision model, individual decision is made collectively with other flock members to reach a consensus about certain behavior (Conradt and Roper, 2005). Conspecific effects are the main factors in decision processes (Dyer et al., 2009b; Kendal et al., 2004). Many works have suggested that animals process stimulus-response functions and perform certain behaviors based on a voting procedure (Sueur et al., 2009) or a quorum of group members (Pratt et al., 2002; Ward et al., 2008). Pillot et al. (2010, 2011) observed and analyzed the departure-following behaviors of sheep: collective movement of certain direction was elicited by an incidental motion of individual. It has been suggested that individual decision to move depends on the already-departed members and non-departed members, as sheep moves one by one instead of simultaneously running if the departure of one sheep successfully triggers the collective movement (Pillot et al., 2011).

Self-propelled model is a widely adopted simulation method to quantitatively interpret the macroscopic states of collective movements (Vicsek et al., 1995). Vortex, finger-like structure and parallel marching are well-known orientational patterns of fish

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school, bird flock and migrating locust (Sumpter, 2006; Vicsek and Zafeiris, 2012). In these groups, individual moves continuously or adjusts position frequently. Therefore, self-propelled models always assume individual has an inherent velocity and propose functions for speed or direction adjustment depending on conspecific effects (Albano, 1996; Aldana et al., 2007; Ginelli and Chaté, 2010; Levine et al., 2000). Social force model is an extension of self-propelled model and proposes a mixture equation of physical and psychological forces influencing pedestrian behavior in a crowd inspired by Newtonian mechanics (Helbing et al., 2000; Helbing and Molnar, 1995). However, social foraging behaviors of sheep share different features and simplex velocity adjustment function may not describe the internal decision process.

In this paper, we therefore propose a friction based social force model to simulate social foraging of sheep and emphasize the importance of individual interactions with food distribution in internal decision process. According to the concept of "social force" (Helbing et al., 2000; Helbing and Molnar, 1995), sheep's motivations to perform certain actions are quantified by different "forces". The instinct of feeding is suggested to represent the individual interaction with currently located patch and quantified by friction force. Individual interactions with other patches are named as attractions of food and quantified by pulling forces. Conspecific effects are usually represented by repulsion–attraction forces between individuals (D'Orsogna et al., 2006; Romanczuk and Schimansky-Geier, 2012). In friction based social force model, agent moves if pulling force and repulsion–attraction force are both larger than friction force and the destination patch can provide enough friction force to resist external forces. The main objectives of this paper include (1) proposing plausible decision process of sheep foraging based on instinct of feeding, (2) simulating social foraging behaviors and testing the effects of instinct of feeding on behaviors of sheep, and (3) mimicking the observed departure-following behaviors. Instinct of feeding is a decision threshold to move or graze. We anticipate that the novel introduction of individual interactions with food distribution in internal decision process helps to understand the formation of collective behaviors in social foraging.

2. Preliminary and modeling methods

2.1. Patches and sheep agent

Computer simulation requires abstracted models of meadow and sheep, as shown in Fig. 1. The meadow is supposed to be a discrete two-dimensional flat and consist of orderly matrix of M patches ($i = 1, 2, \ldots, M$). The quantity and quality of grass in patch i are jointly named as the value of grass in patch i and represented by positive number R_i. The sheep (agent and sheep are interchangeable concepts in the following) has a facing direction and visual acuity range. Visual acuity range is a fan-shaped area with radius r and angular resolution $[-\theta/2, \theta/2]$, which is similar to the representation of visual information in behavioral heuristics research (Moussaïd et al., 2011). The facing direction bisects the visual acuity angle. A similar concept is mentioned as "desired direction" in the research of spatial dynamics of animal groups (Couzin et al., 2002). We use c_i and p_a to represent the positional coordinates of patch i and agent a.

The agent moves between patches within the visual acuity range and consumes a part of the "forage grass". Time is partitioned into discrete time steps with unit interval spacing. If agent a is in patch i in time t, $p_a(t)$ equals c_i; and if agent a moves to patch j in time t', $p_a(t')$ equals c_j. Then, agent a changes facing direction as follows:

$$f_a(t') = \frac{p_{a(t')} - p_{a(t)}}{\left|p_{a(t')} - p_{a(t)}\right|} = \frac{c_j - c_i}{\left|c_j - c_i\right|} \tag{1}$$

When agent moves, the facing direction is changed and patches within visual acuity range are updated. In this way, agent may explore new patches. Meanwhile, the agent is abstracted as a particle, with no volume (Couzin et al., 2002; Sumpter, 2006; Vicsek et al., 1995).

2.2. Three forces in social foraging

In the following, three forces that influence the decision of agent a will be introduced. Friction force is the product of friction coefficient and the value of grass. With reference to related works (Ginelli and Chaté, 2010; Levine et al., 2000; Romanczuk and Schimansky-Geier, 2012), pulling force of patch and repulsion–attraction force of conspecifics are calculated as forms of natural exponential functions.

2.2.1. Friction force

The instinct of feeding represents individual direct interaction with currently located patch and is the main reason for grazing behavior. The "friction coefficient" represents the magnitude of instinct and is denoted by μ. When agent a is currently located in patch i, patch i provides the friction force for agent a:

$$F_f(a, i) = R_i \times \mu_a \tag{2}$$

2.2.2. Pulling force

Generally, agent tends to move to a patch which can provide abundant food. Patch i within the visual acuity range shows an attractive effect, which is represented by pulling force:

$$F_p(a, i) = \left[\exp\left(\frac{R_i}{\tau_1}\right) - 1\right] \times \frac{c_i - p_a}{\left|c_i - p_a\right|} \tag{3}$$

τ_1 is constant and determines the steepness of the pulling force.

2.2.3. Repulsion–attraction force

Consecifics effects are usually represented by repulsion–attraction force and a "comfortable" distance is always assumed to be the dividing line between repulsive force and attractive force (D'Orsogna et al., 2006; Romanczuk and Schimansky-Geier, 2012). If distance between two members is less than the comfortable distance, repulsive force drives agents away from each other. Attractive force prevents sheep from being separated from the flock. Therefore, the repulsion–attraction force F_e (a, b) is a piecewise function with value d which denotes the distance between agent a and b.

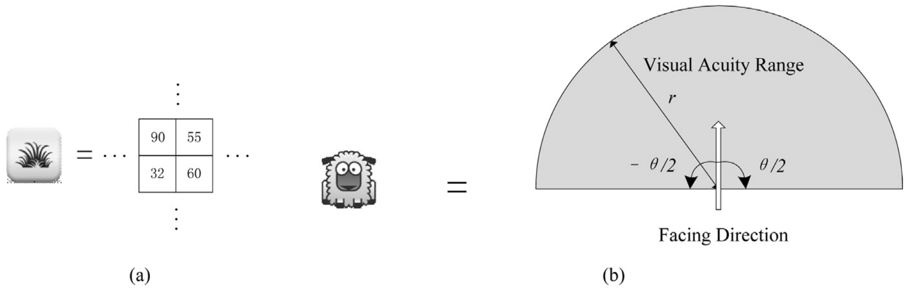
$$\begin{aligned} F_e(a, b) &= \left[\exp\left(\left|\frac{d - d_c}{\tau_2}\right|\right) - 1\right] \times \frac{p_b - p_a}{\left|p_b - p_a\right|}, \quad d > d_c \\ F_e(a, b) &= \left[\exp\left(\left|\frac{d - d_c}{\tau_2}\right|\right) - 1\right] \times \frac{p_a - p_b}{\left|p_b - p_a\right|}, \quad 0 < d < d_c \\ F_e(a, b) &= 0, \quad d = d_c \end{aligned} \tag{4}$$

where d_c is constant and denotes the comfortable distance, and τ_2 is also constant and determines the steepness of repulsion–attraction force. Meanwhile, we have:

$$F_e(a, b) = -F_e(b, a), \quad d > 0 \tag{5}$$

If agent a and b are in the same patch ($d = 0$), we assume that the directions of repulsion–attraction forces depend on the facing directions of agents:

$$\begin{aligned} F_e(a, b) &= \left[\exp\left(\left|\frac{d - d_c}{\tau_2}\right|\right) - 1\right] \times f_a \\ F_e(b, a) &= \left[\exp\left(\left|\frac{d - d_c}{\tau_2}\right|\right) - 1\right] \times f_b \end{aligned} \tag{6}$$



(a) (b)

Fig. 1. Abstracted models of meadow and sheep: (a) patches; (b) sheep agent.

The repulsion–attraction force of flock is the sum of repulsion–attraction forces between flock members and G is the set of flock members:

$$F_e(a) = \sum_{b \neq a}^{b \in G} F_e(a, b) \tag{7}$$

2.3. The model

The elaboration of friction based social force model requires two crucial rules: (1) agent decides to move if repulsion–attraction force and pulling force are both larger than friction force; (2) agent moves to a certain patch which can provide enough friction force to resist external forces. With regard to the first rule, friction force performs like a decision threshold to move or feed because sheep spends most of time on grazing although repulsion–attraction forces and pulling forces coexist at any moment. The second rule defines positional adjustment of sheep: the selected patch should satisfy the instinct of sheep to stay and feed. Friction based social force model contains four decision modules to formalize the two rules as shown in Fig. 2.

Module A and B are the formalizations of the first rule. In each time step, agent a consumes a part of grass in currently located patch i, and naturally this consumption reduces the friction force F_f (a, i). In module A, agent a remains at rest if the repulsion–attraction force of group is less than the friction force of patch i. If the repulsion–attraction force of group is larger than the friction force, agent may decide to move and decision process is shifted to module B. Otherwise, agent decides to feed on current patch. In module B, the facing direction of agent a is modified to the unit vector of repulsion–attraction force. Ω_a is a set of patches which are within the visual acuity range of agent a. If $F_f(a, i)$ is larger than the pulling force of patch j, patch j is removed from Ω_a. After the traversal of every element in Ω_a, agent remains at rest if Ω_a is empty. Otherwise, decision process is shifted to module C.

According to the second rule, destination patch should provide the largest pulling forces among the rest elements in Ω_a and enough friction force to resist repulsion–attraction force. $F_f(a, j \in \Omega_a)$ is the friction force if agent a stands in patch j. The repulsion–attraction force which will influence agent a in patch j is calculated by Eq. (8).

$$F_e(a|j) = \sum_{b \neq a}^{b \in G} F_e(j, b) \tag{8}$$

If $F_f(a, j \in \Omega_a)$ is less than $\boldsymbol{F}_e(a \mid j)$, patch j is removed from set Ω_a. After the second traversal, agent a moves to the patch which provides the largest pulling force. If Ω_a is empty, module D is performed which means that agent has to move according to the first rule of our model while no patch within visual acuity range meets the second rule. Agent a updates Ω_a and then moves to a patch where it is affected by minimum repulsion–attraction force.

3. Simulation and analysis

3.1. Model implementation

The friction based social force model developed for social foraging of interacting sheep has been implemented on a computer. The simulated "meadow" is assumed to be 60 m width and 60 m

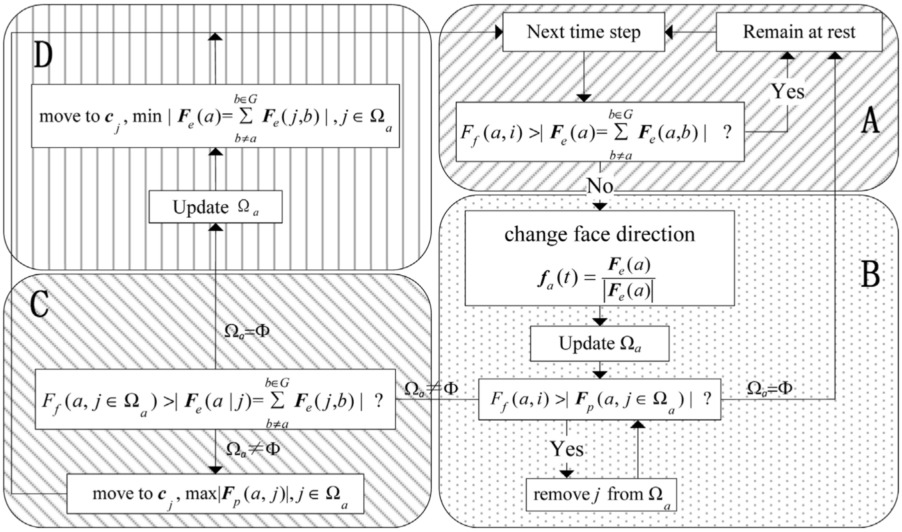
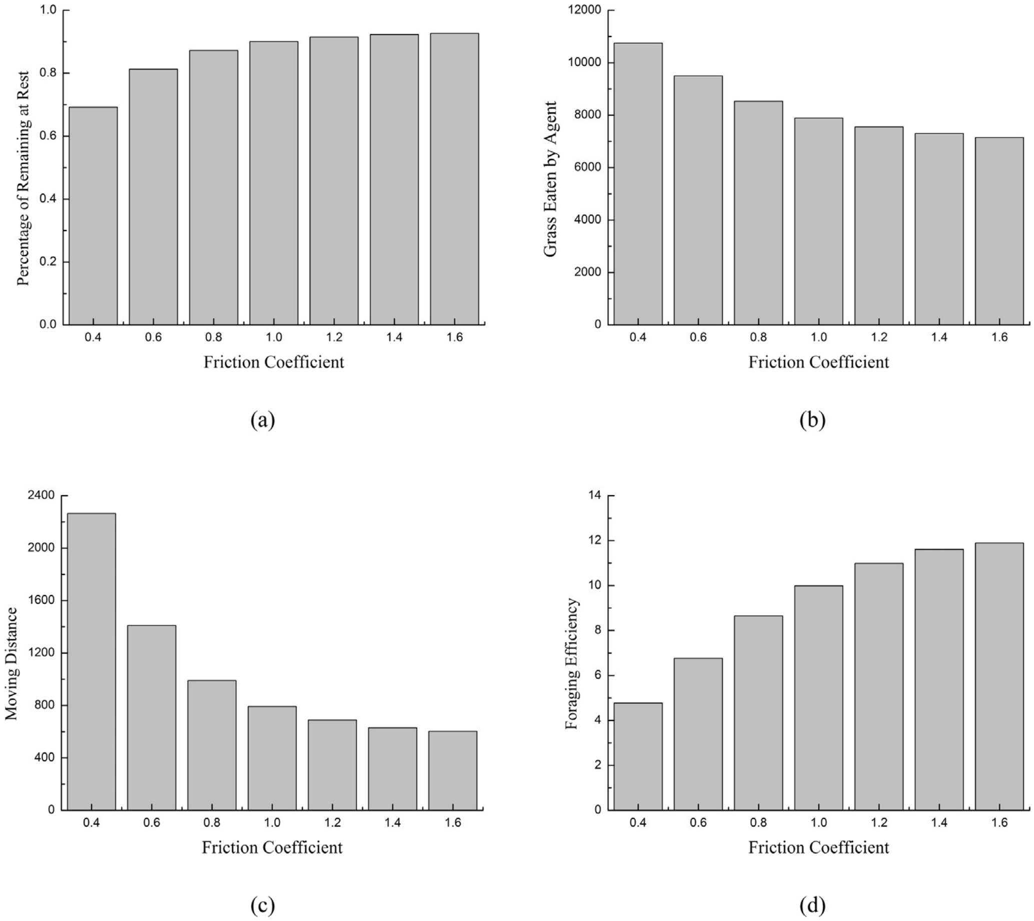


Fig. 2. Decision modules of friction based social force model.



(a) (b)

(c) (d)

Fig. 3. Effects of instinct of feeding on (a) percentage of remaining at rest, (b) benefit, (c) moving distance, and (d) foraging efficiency.

length, and contains 600 × 600 patches of the same size. Some real filed data indicate that animals continuously prefer to eat the highest parts of sward (Baumont et al., 2004). Therefore, the value of grass in each patch is assumed to be different and follow uniformly random distribution which is between 0 and a maximum value. In this paper, the standard maximum value of grass is 150. Food in simulated meadow is very “abundant” if the maximum value is larger than 150 and is “short” if the maximum value is less than 150. In each time step, agent is assumed to consume one-tenth grass in a patch, to distinguish “gobbling” from “nibbling” (Allden and McDWhittaker, 1970). Each simulation contains 1000 time steps and 40 replications.

The comfortable distance and the visual acuity radius are both set as 12 since the median of nearest neighbor distance is about 1.2 m reported by Pillot et al. (2010). According to turning angles reported by de Knegt et al. (2007), the visual acuity angle is set as π. The standard friction coefficient is set to 1. The largest pulling force of patch and the repulsion–attraction force between two agents in the same patch are assumed to approach the largest standard friction force, 150. Finally, the steepness of pulling force is 30, and the steepness of elastic force is 2.4. The number of sheep (N, flock size) is fixed 8, as no more than eight sheep are used in many real field experiments (de Knegt et al., 2007; Michelena et al., 2009; Pillot et al., 2010, 2011).

3.2. Major indexes of social sheep foraging

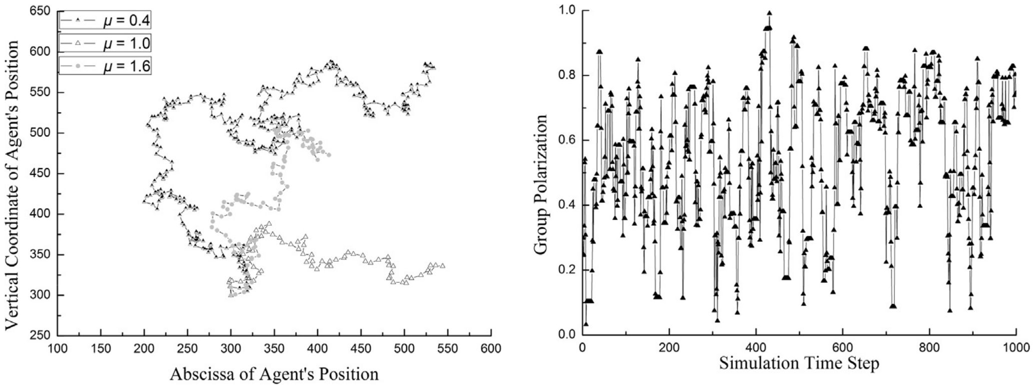
Effects of instinct of feeding on social sheep foraging are analyzed by varying friction coefficients and maximum values of grass in different trials. Percentage of remaining at rest, benefit (grass eaten by sheep), moving distance and trajectory are used to describe the behaviors of agent. Foraging efficiency is an important element in social foraging which is simply defined as the ratio of benefit to moving distance. Higher foraging efficiency means agent gains large quantities of food at a low caloric cost (Hainsworth, 1974).

Sinuosity is used to estimate the tortuosity of an animal’s path (Benhamou, 2004). Accordingly, we define the sinuosity of one time movement as the ratio of the turning angle of facing directions to the distance of one time movement. The sinuosity of agent’s path is the average of all movements’ sinuosity. Higher sinuosity of path indicates larger turning angles and shorter step lengths during migration.

Group polarization is a common global property to indicate the degree of alignment among individuals in collective movements (Couzin et al., 2002; Niizato and Gunji, 2011). Accordingly, we define the group polarization of all agents in simulated social foraging by Eq. (9):

$$\varphi_{\text{group}}(t) = \frac{1}{N}\left|\sum_{a=1}^{N} f_a(t)\right| \tag{9}$$

The parameter φ_{group} represents the group polarization of all agents. If facing directions of all agents are nearly the same, φ_{group} approaches 1.0 at a maximum. Oppositely, group polarization is zero if facing directions of agents are completely different.



(a) (b)

Fig. 4. (a) Trajectories of agents with $\mu = 0.4$, 1.0 and 1.4; (b) group polarization of all moving agents with $\mu = 1.0$.

3.3. Identical agents and food density

First, agents in the flock have identical friction coefficient and maximum values of grass are all 150. In different trials, friction coefficients are varied from 0.4 to 1.6. Fig. 3(a) describes that agent keeps most of time stationary and this simulation result accords with real field observation (Pillot et al., 2010). From Fig. 3(a)–(c), we can find that, as friction coefficient increases, benefit and moving distance of agent both decrease and agent spends more time keeping stationary to feed. It is because that agent tends to explore more new abundant patches with less friction coefficient. Fig. 3(b) and (c) also describe that individual generally needs to explore more areas to obtain more food. However, Fig. 3(d) shows that the foraging efficiency increase as the friction coefficient increases. It means that with the present food density, exploring much more patches is not the most reasonable foraging behavior for sheep because the incremental benefit caused by low friction coefficient is disproportionate to the incremental caloric cost (moving distance).

Fig. 4(a) shows the tortuous trajectories of agents and Fig. 4(b) describes the large fluctuation of group polarization during social sheep foraging. The spontaneous movement of sheep to feed on new patch with abundant food is the main reason of the tortuous motion path and fluctuation of group polarization. Because of the instinct of feeding, sheep prefers to keep stationary to feed as agent decides to move only if conspecifics effects and attractive effects of other patches are both larger than the friction force. However, due to the nearly exhausted food in current location, each agent can behave spontaneous movement while the others are all grazing which accords with real observation (Pillot et al., 2010). The destination patch of the spontaneous movement may be at an angle to present facing direction. Meanwhile, motion changes the facing direction of sheep and provides opportunities to explore other patches within visual acuity range. The agent who behaves spontaneous movement may trigger the collective movement of whole flock in the same direction or may decide to follow the others after several time steps. Therefore, during simulated social foraging, group polarization of agents oscillates so much and the transient peak value of φ_{group} generally indicates that the collective movement of certain direction is motivated by abundant food in patches.

3.4. Identical agents and different food densities

Then, the effects of instinct of feeding on foraging efficiency and sinuosity of path are further investigated by varying the maximum values of grass. Fig. 5(a) describes that agents with stronger instinct of feeding have greater foraging efficiency especially when maximum value of grass is 200. Agent can gain enough food without moving a long distance when food is abundant. When maximum value of grass is 50 and food is short, the foraging efficiencies of agents with different friction coefficients tend to be similar and all agents have to move much longer distance to obtain enough food. Behaviors of agents with less friction coefficient may be reasonable when food is short, because less friction coefficient encourages individuals to explore more areas and consequently increases the potential opportunity to find new foraging sites.

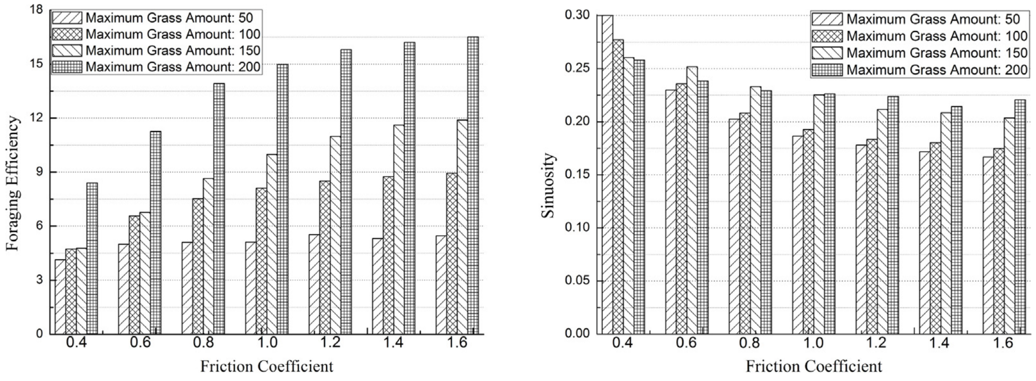
Fig. 5(b) shows that sinuosity of path decreases as the friction coefficient increases and path is more tortuous when food is abundant. For large herbivores such as goats, movement patterns of individuals in a flock depend on different food densities in habitat: slow-tortuous movement when food density increases and fast-straight migration when food is short (de Knegt et al., 2007). Simulation result in Fig. 5(b) generally accords with de Knegt et al.'s conclusion.

3.5. Different agents and identical food density

In addition, we investigate the effect of flock composition with different instincts of feeding on foraging efficiency. Maximum values of grass are set as 150. Agents are divided into two subgroups according to friction coefficients: "active" subgroup with $\mu = 0.6$ and "inactive" subgroup with $\mu = 1.4$. We use n_1 and n_2 to separately represent the numbers of agents in active and inactive subgroups, and then modulate n_1 and n_2 and record the foraging efficiencies of individuals in each subgroup. Fig. 6 shows that agents in mixed subgroups have higher foraging efficiency than identical agents in either active or inactive flocks. It suggests positive effect of flock composition of different sheep on social foraging. Interestingly, Michelena et al. (2009) suggested that individual variability may help to minimize the interference competition during social foraging and analyze the distribution of sheep in patchy resources. For other species, Dyer et al.'s also found a potential feeding advantage of a mix shoal containing "bold" and "shy" guppies (Dyer et al., 2009a).

3.6. Mimicking departure-following behaviors

At last, we test our model to mimic the departure-following behaviors of social sheep foraging: collective movement of certain direction was elicited by an incidental motion of individual. Pillot et al. (2010, 2011) first trained some sheep to move toward a color board responding to a sound cue, and then gathered one



(a) (b)

Fig. 5. Effects of instinct of feeding with different maximum values of grass on: (a) foraging efficiency and (b) sinuosity.

trained sheep with most seven untrained sheep (naive sheep). They reported that, after the cue sounded, trained sheep moved to the color board, and naive sheep followed. In the simulation, one agent is initialized as “trained” sheep, and seven agents taking friction based social force model are set up as “naive” sheep. Trained sheep moves two patches every 5 steps in a constant direction and friction coefficient of naive sheep is fixed 1.

Fig. 7(a) shows the typical trajectories of agents performing departure-following behaviors and only two agents are selected to avoid a mess. The repulsion–attraction force plays a fundamental role in the formation of collective movement. As the trained sheep gradually moves away from the flock, repulsion–attraction forces of some naive sheep continuously increase until friction forces are overcome. Consequently, naive sheep decides to follow the departed sheep to reduce repulsion–attraction force. It can be found that beside the following behaviors, naive sheep also explore patches surrounding the motion route of trained sheep. However, comparing with the trajectory of naive sheep with no trained sheep in the flock, the path of naive led by trained sheep is less sinuous. As shown in Fig. 7(b), sinuosity of naive sheep's path is greatly reduced when food is short and one trained sheep is added into flock. For other kinds of animals, such as fish (Reebs, 2000) or elephant (Wittemyer et al., 2005), the role of trained sheep is like the special individuals in a group who have pertinent knowledge about the foraging sites or water points. In the shortage of food or water, informed leader can reduce the distance and tortuosity of migration.

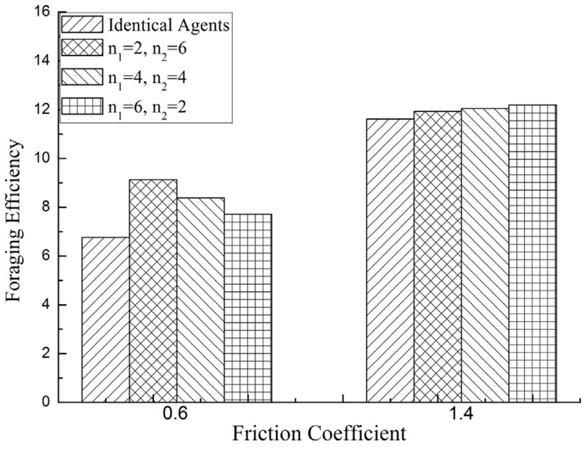


Fig. 6. Effect of flock composition with different instincts of feeding on foraging efficiency.

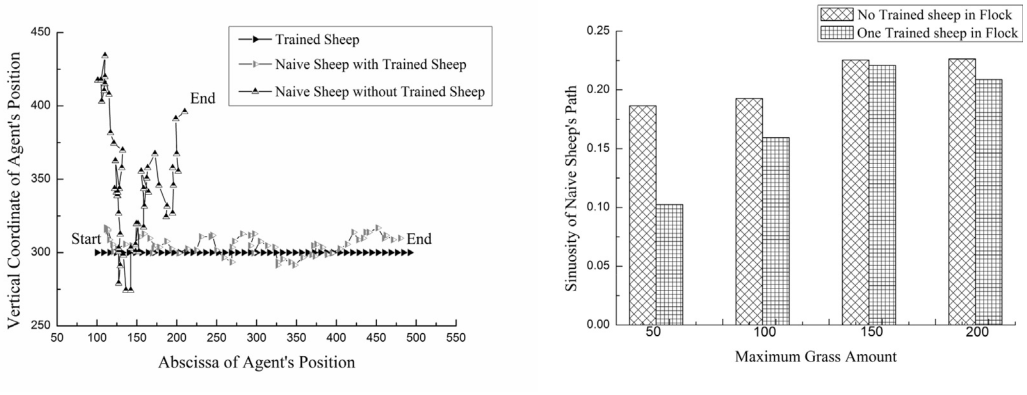
4. Discussion

Our model emphasizes the importance of interactions with food distribution and exhibits numerical simulations of social foraging behaviors. Instinct of feeding is individual direct interaction with currently located patch and is a decision threshold to move or graze. Conspecific effects and attraction of food are both motivations to move. The two crucial rules and four decision modules of our model briefly portray the decision-making of sheep in social foraging. The main innovation of our model comparing with traditional social force model (Helbing et al., 2000) and self-propelled model (Vicsek et al., 1995) is that each agent can behave spontaneous movement ignoring the grazing behaviors of the others and the flock can still move collectively. It has been shown that the spontaneous movement of sheep to feed on new patch is the main reason of the tortuous motion and fluctuation of group polarization.

Friction based social force model could provide two plausible reasons to explain why sheep feed on less-preferred patches (Dumont and Boissy, 2000; Sibbald and Hooper, 2004). The first one is that the repulsion–attraction force of flock is very large if sheep move to preferred patches in the case of current locations of other flock members. Thus, although the pulling forces of preferred patches may be the largest, sheep will not move to preferred patches which are far away from most flock members. The second one is that current repulsion–attraction force is near zero as sheep keeps comfortable distances with other flock members. Then, sheep will not adjust position unless food in currently located patch is exhausted or other flock members move.

Meanwhile, the modulations of parameters and redesigning of decision modules in friction based social force model provide an opportunity to formalize the “personality” traits in the study of behavioral variation in animals (Dyer et al., 2009a; Michelena et al., 2009; Reaney and Backwell, 2007). Flock composition with different friction coefficients represents one kind of “personality” traits of sheep in a flock: with less friction coefficient, sheep becomes more “active” and tends to explore new patches. The simulation results also demonstrate that more exploring behaviors are less efficient when food is abundantly distributed in foraging sites. However, when food is short, more exploring behaviors and long moving distances are needed to get enough food.

Moreover, the tortuosity of agent's motion path depends on the instinct of feeding and food density which are both related to individual interactions with food distribution. Our model provides another way to simulate the movement patterns of large herbivores besides the lévy walk (de Knegt et al., 2007). We suppose that one agent spontaneously move to a patch which can provide abundant food and is far from the flock while other agents remain at



(a)

(b)

Fig. 7. (a) Trajectories of trained sheep and naive sheep with maximum value of grass = 50 and $\mu = 1.0$; (b) sinuosity of agent's path with different maximum values of grass and $\mu = 1.0$.

current patches to feed. A moment later, one agent in flock decides to move. Because repulsion–attraction force influences the decision to select destination patch, the agent may move to a patch which is a compromised between the departed agent and other flock members. Then, other agents decide to move following the same process. Consequently, the direction of collective movement may be different from the moving direction of the departed agent. However, if patches along the moving direction of the departed agent can all provide abundant food, it can be predicted that other flock members will follow the departed agent mostly due to the attraction of food.

In this paper, we suppose that sheep has basic capabilities to evaluate external stimuli and personal instinct, in the case that we simplify the model of sheep-agent and meadow and focus on the decision process of sheep to move or graze. Sheep decides to perform certain behaviors not only depending on observed information from environment but also its intrinsic interactions with environment. The shepherd/dog and obstacle can also influence sheep's movement and other behaviors such as rumination, rest and trail-following should be considered in the future. Therefore, more realistic agent models and simulation models are needed to reproduce how individual mind, strategy or behavior evaluates (Cao, 2010; de Weerd et al., 2013; Niizato and Gunji, 2011) and elucidate the formations of other collective behaviors such as fission-fusion of huge flock (Couzin and Laidre, 2009). Friction force ties different external stimuli together and can be widely used when behaviors of individual in a group suddenly change. Our model emphasizes the importance of individual interactions with food distribution and could provide new insights into the mechanism governing internal decision process in the thriving multidisciplinary area.

Acknowledgments

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