Role of Starvation on Foraging Dynamics

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Abstract.

We outline an event-driven simulation approach for the foraging model, which involves a resource that renews by logistic growth, as well as two classes of foragers—full and hungry. Full foragers reproduce at a fixed rate and are not vulnerable to mortality. However, a full forager can starve when resources are scarce; conversely, a hungry forager can become full when the resource is abundant. Hungry foragers do not reproduce and die at rate μ.

1. The Model

We assume that foragers can exist in two discrete states—full and hungry. Full foragers F are those that have just encountered and consumed a unit of resource R. On the other hand, a full forager that does not encounter a resource as it wanders is converted into a hungry forager H with rate σ. Whenever a forager, either full or hungry, encounters resources, one unit of the resource is consumed. If the forager was hungry, it is recruited into the full population with rate ρ. During the time that a forager is hungry, it dies with a fixed mortality rate μ, while full foragers do not experience mortality risk. Furthermore, full foragers reproduce with rate λ. Finally, we assume that, in the absence of foragers, the underlying resource undergoes logistic growth, with growth rate α and carrying capacity equal to one.

According to these processes and also under the assumption that the densities of full foragers, hungry foragers, and resources (also denoted by F, H, and R, respectively) are perfectly mixed, they evolve according to the rate equations:

$$\begin{aligned}
\dot{F} &= \lambda F + \rho R H - \sigma(1-R)F\,,\\
\dot{H} &= \sigma(1-R)F - \rho R H - \mu H\,,\\
\dot{R} &= \alpha R(1-R) - R(F+H),
\end{aligned} \tag{1}$$

where the overdot denotes time derivative.

We now outline our event-driven algorithm to simulate these rate equations. We will also generalize to the situation where the full and hungry foragers undergo diffusion with possibly different diffusion coefficients. Suppose that the system at some time consists of N_F individuals of type F, N_H individuals of type H, and N_R individuals of type R. The total number of particles $N = N_F + N_H + N_R$.

In each simulation step an individual is picked: a full individual is picked with probability N_F/N, a hungry individual is picked with probability N_H/N, and a individual resource is picked with probability N_R/N. If an F is picked, it reproduces at rate λ and becomes hungry with rate $\sigma(1 - R)$. If an H is picked, it becomes full with rate ρR and dies with rate μ. Finally, if an R is picked, it grows with rate $\alpha(1-R)$ and is eaten with rate $(F + H)$. Thus the total rate for each individual event is

$$\mathcal{R} = F\big[\lambda + \sigma(1 - R)\big] + H\big[\rho R + \mu\big] + R\big[\alpha(1 - r) + (F = H)\big]\,. \tag{2}$$

Now let's look at how the system evolves according to the various constituent processes. If an F is picked, then it may either reproduce or go hungry according to the processes outlined above. That is:

$$\begin{aligned} &\text{growth, prob. } \lambda/\mathcal{R} && N_F \to N_F{+}1\,, \\ &\text{starve, prob. } \sigma(1 - R)\mathcal{R} && N_F \to N_F{-}1,\ N_S \to N_S{+}1\,. \end{aligned}$$

Similarly, if an H is picked, it may either become full or die following the processes given above. That is:

$$\begin{aligned} &\text{become full, prob. } \rho R/\mathcal{R} && N_H \to N_H{-}1,\ N_F \to N_F{+}1\,, \\ &\text{die, prob. } \mu/\mathcal{R} && N_H \to N_H{-}1\,. \end{aligned}$$

Finally, if an R is picked, it may either grow or be eaten following the processes given above. That is:

$$\begin{aligned} &\text{grow, prob. } \alpha(1{-}R)/\mathcal{R} && N_R \to N_R{+}1\,, \\ &\text{eaten, prob. } (F{+}S)/\mathcal{R} && N_R \to N_R{-}1\,. \end{aligned}$$

With these steps, let's now determine the change in the expected number of full individuals in a single event. This change is

$$\Delta N_F = \left[\frac{N_F}{N}\,(\lambda - \sigma(1 - R)) + \frac{N_S}{N}\rho R\right]/\mathcal{R}\,. \tag{3a}$$

Consequently, the change in the density of full individuals simply is

$$\Delta F = \left[\frac{N_F}{N}\,(\lambda - \sigma(1 - R)) + \frac{N_S}{N}\rho R\right]/N\mathcal{R}\,. \tag{3b}$$

Thus is we take the time step to be $\Delta t = (N\mathcal{R})^{-1}$, the above reduces to the rate equation (1) for F.

In a similar fashion, the change in the expected number of hungry individuals in a single event is given by

$$\Delta N_H = \left[-\frac{N_H}{N}\,(\mu + \rho R) + \frac{N_F}{N}\sigma(1 - R)\right]/\mathcal{R}\,, \tag{4a}$$

so that the change in the density of hungry individuals simply is

$$\Delta H = \left[-\frac{N_H}{N}\left(\mu + \rho R\right) + \frac{N_F}{N}\sigma(1-R)\right]/N\mathcal{R}\,. \tag{4b}$$

Finally, the change in the expected number of individual resources in a single event is given by

$$\Delta N_R = \left[\frac{N_R}{N}\left(\alpha(1-R)\right) - \frac{N_F}{N} - \frac{N_H}{N}\right]/\mathcal{R}\,, \tag{5a}$$

so that the change in the density of resources is

$$\Delta R == \left[\frac{N_R}{N}\left(\alpha(1-R)\right) - \frac{N_F}{N} - \frac{N_H}{N}\right]/N\mathcal{R}\,. \tag{5b}$$