1 Likelihood

- S_t: the t-th sample.
- $S_T^{in} = \bigcup_{t=1}^{T} S_t$: set of sampled individuals up to and including T-th sample.
- S_T^{out}: set of individuals that has not been sampled after T sample draws. ($S_T^{out} \cap S_T^{in} = \emptyset$).
- $\mathcal{P} = S_T^{in} \cup S_T^{out}$: the entire population.
- $d_{i(T)}$: number of samples that contained individual i:

$$d_{i(T)} = \sum_{t=1}^{T} \mathbb{1}\{i \in S_t\}$$

Assuming that samples are drawn independently:

$$\mathbb{E}[d_{i(T)}] = \sum_{t=1}^{T} \pi_i = T\pi_i$$

where π_i denotes inclusion probability of i. This suggests estimating π_i by

$$\hat{\pi}_i = \frac{d_{i(T)}}{T} \quad \text{or} \quad \hat{\pi}_i = \frac{1 + d_{i(T)}}{1 + T} \tag{1}$$

where the latter comes from enforcing that probabilities be non-zero. Note that in this case $\hat{\pi}_i = \frac{1}{1+T} \forall i \in S_T^{out}$.

Consider the problem from the Bayesian perspective. Assume Beta prior for inclusion probabilities:

$$\pi_i \sim Be(\alpha, \beta)$$

Then

$$\mathbb{E}[\sum_{i \in \mathcal{P}} \pi_i] = \sum_{i \in \mathcal{P}} \frac{\alpha}{\alpha + \beta} = |\mathcal{P}| \frac{\alpha}{\alpha + \beta} = (|S_T^{out}| + |S_T^{in}|) \frac{\alpha}{\alpha + \beta}$$

Let $n_t := |S_t|$ be the sample size. While we assume independent replications of the same sampling scheme, depending on the chosen scheme, it is possible for n_t to be random. However, for simplicity, assume here that $n_t = n$ is fixed.

$$\mathbb{E}[\sum_{i \in \mathcal{P}} \pi_i] = \mathbb{E}[n_t] \Leftrightarrow (|S_T^{out}| + |S_T^{in}|) \frac{\alpha}{\alpha + \beta} = n \tag{2}$$

(in case of random n_t, we can estimate $\mathbb{E}[n_t]$ by $T^{-1} \sum_{t=1}^{T} n_t$).

Condition (2) will be the constraint for our model.

The likelihood would be

$$d_{i(T)} | \pi_i \sim Bin(T, \pi)$$

Then the posterior distribution is

$$\begin{aligned}
f(\pi_i|d_{i(T)}=k) &= \frac{\mathbb{P}(d_{i(T)}=k|\pi_i)f(\pi_i)}{\mathbb{P}(d_{i(T)}=k)} \\
&\propto \pi_i^k(1-\pi_i)^{T-k}\pi_i^{\alpha-1}(1-\pi_i)^{\beta-1} \\
&= \pi_i^{\alpha+k-1}(1-\pi_i)^{\beta+T-k-1} \\
&\Rightarrow \pi_i|d_{i(T)}=k \sim Be(\alpha+k,\beta+T-k) \\
&\Rightarrow \mathbb{E}[\pi_i|d_{i(T)}=k] = \frac{\alpha+k}{\alpha+\beta+T}
\end{aligned}$$

The marginal likelihood is:

$$\begin{aligned}
\mathbb{P}(d_{i(T)}=k) &= \int_0^1 f(\pi_i,d_{i(T)})d\pi_i = \int_0^1 \mathbb{P}(d_{i(T)}=k|\pi_i)f(\pi_i)d\pi_i \\
&= \binom{T}{k}\frac{B(\alpha+k,\beta+T-k)}{B(\alpha,\beta)}
\end{aligned}$$

Note that we never observe $d_{i(T)}=0$. The observed frequences $d_{i(T)}>0$ for $i\in S_T^{in}$ follow a truncated distribution:

$$\begin{aligned}
\mathbb{P}(d_{i(T)}=k|d_{i(T)}>0) &= \begin{cases} \frac{\mathbb{P}(d_{i(T)}=k)}{1-\mathbb{P}(d_{i(T)}=0)}, & \text{if } k>0 \\ 0, & \text{otherwise} \end{cases} \\
&= \begin{cases} \binom{T}{k}\frac{B(\alpha+k,\beta+T-k)}{B(\alpha,\beta)-B(\alpha,\beta+T)}, & \text{if } k>0 \\ 0, & \text{otherwise} \end{cases}
\end{aligned}$$

Following empirical Bayes approach, maximise the marginal likelihood to obtain hyperparameters α and β.

$$\begin{aligned}
L(\alpha,\beta) &:= L(\alpha,\beta;T,d_{i(T)}=k_i\forall i\in S_T^{in}) \\
&\overset{indep}{=} \prod_{i\in S_T^{in}}\binom{T}{k_i}\frac{\Gamma(\alpha+k_i)\Gamma(\beta+T-k_i)}{\Gamma(\alpha+\beta+T)}\cdot\frac{1}{\frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)}-\frac{\Gamma(\alpha)\Gamma(\beta+T)}{\Gamma(\alpha+\beta+T)}} \\
&= \prod_{i\in S_T^{in}}\binom{T}{k_i}\frac{\Gamma(\alpha+k_i)\Gamma(\beta+T-k_i)\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)\Gamma(\alpha+\beta+T)-\Gamma(\alpha)\Gamma(\beta+T)\Gamma(\alpha+\beta)}
\end{aligned} \tag{3}$$

Equation (3) is to be maximised subject to (2). The optimisation problem can be simplified by solving the constraint for β and plugging into the objective function:

$$\begin{aligned}
&\max_{\alpha,\beta} L(\alpha,\beta) \quad \text{s.t.} \quad |\mathcal{P}|\frac{\alpha}{\alpha+\beta}=n \\
&\qquad\qquad \Leftrightarrow \beta = \left(\frac{|\mathcal{P}|}{n}-1\right)\alpha := q\alpha \\
&\Rightarrow \max_{\alpha,q} L(\alpha,q)
\end{aligned}$$

$$L(\alpha,q) \overset{wrt.\alpha,q}{\propto} \prod_{i\in S_T^{in}}\frac{\Gamma(\alpha+k_i)\Gamma(q\alpha+T-k_i)\Gamma(\alpha+q\alpha)}{\Gamma(\alpha)\Gamma(q\alpha)\Gamma(\alpha+q\alpha+T)-\Gamma(\alpha)\Gamma(q\alpha+T)\Gamma(\alpha+q\alpha)}$$

Using the recursive formula of gamma function $\Gamma(x) = (x-1)\Gamma(x-1)$ and the fact that $T, k_i \in \mathbb{N}_0 := \mathbb{N} \cup \{0\}$ allows us to rewrite the marginal likelihood as:

$$
\begin{aligned}
L(\alpha, q) \propto & \prod_{i \in S_T^{in}} \frac{\Gamma(\alpha)\Gamma(q\alpha)\Gamma(\alpha + q\alpha)}{\Gamma(\alpha)\Gamma(q\alpha)\Gamma(\alpha + q\alpha)} \\
& \times \frac{\prod_{j=1}^{k_i}(\alpha + k_i - j) \prod_{j=1}^{T-k_i}(q\alpha + T - k_i - j)}{\prod_{j=1}^{T}(\alpha + q\alpha + T - j) - \prod_{j=1}^{T}(q\alpha + T - j)} \\
& = \frac{\prod_{j=1}^{k_i}(\alpha + k_i - j) \prod_{j=1}^{T-k_i}(q\alpha + T - k_i - j)}{\prod_{j=1}^{T}(\alpha + q\alpha + T - j) - \prod_{j=1}^{T}(q\alpha + T - j)}
\end{aligned}
$$

The product terms are computationally expensive to calculate, as even small values of T and k_i will yield extremely large quantities. Taking logarithms alleviates the problem with the numerator but not the denominator. Therefore, further simplification of the marginal likelihood is required.

$$
\begin{aligned}
L(\alpha, q) \propto & \frac{\prod_{j=1}^{k_i}(\alpha + k_i - j) \prod_{j=1}^{T-k_i}(q\alpha + T - k_i - j)}{\prod_{j=1}^{T}(\alpha + q\alpha + T - j) - \prod_{j=1}^{T}(q\alpha + T - j)} \\
= & \prod_{i \in S_T^{in}} \frac{\prod_{j=1}^{k_i}(\alpha + k_i)(1 - \frac{j}{\alpha + k_i}) \prod_{j=1}^{T-k_i}(q\alpha + T)(1 - \frac{k_i + j}{q\alpha + T})}{\prod_{j=1}^{T}(q\alpha + T)(1 - \frac{j - \alpha}{q\alpha + T}) - \prod_{j=1}^{T}(q\alpha + T)(1 - \frac{j}{q\alpha + T})} \\
= & \prod_{i \in S_T^{in}} \left(\frac{\alpha + k_i}{q\alpha + T} \right)^{k_i} \frac{\prod_{j=1}^{k_i}(1 - \frac{j}{\alpha + k_i}) \prod_{j=1}^{T-k_i}(1 - \frac{k_i + j}{q\alpha + T})}{\prod_{j=1}^{T}(1 - \frac{j - \alpha}{q\alpha + T}) - \prod_{j=1}^{T}(1 - \frac{j}{q\alpha + T})} \\
= & \left[\prod_{j=1}^{T} \left(1 - \frac{j - \alpha}{q\alpha + T} \right) - \prod_{j=1}^{T} \left(1 - \frac{j}{q\alpha + T} \right) \right]^{-|S_T^{in}|} \\
& \times \prod_{i \in S_T^{in}} \left[\left(\frac{\alpha + k_i}{q\alpha + T} \right)^{k_i} \prod_{j=1}^{k_i} \left(1 - \frac{j}{\alpha + k_i} \right) \prod_{j=1}^{T-k_i} \left(1 - \frac{k_i + j}{q\alpha + T} \right) \right]
\end{aligned} \tag{4}
$$

The corresponding marginal log-likelihood is

$$
\begin{aligned}
l(\alpha, q) := & \log L(\alpha, q) \\
= & \; const - |S_T^{in}| \log \left[\prod_{j=1}^{T}(1 - \frac{j - \alpha}{q\alpha + T}) - \prod_{j=1}^{T}(1 - \frac{j}{q\alpha + T}) \right] \\
& - \log(q\alpha + T) \sum_{i \in S_T^{in}} k_i + \sum_{i \in S_T^{in}} k_i \log(\alpha + k_i) \\
& + \sum_{i \in S_T^{in}} \sum_{j=1}^{k_i} \log(1 - \frac{j}{\alpha + k_i}) + \sum_{j=1}^{T-k_i} \log(1 - \frac{k_i - j}{q\alpha + T})
\end{aligned} \tag{5}
$$

Derivatives:

$$
\begin{aligned}
\frac{\partial l(\alpha,q)}{\partial \alpha} =& -|S_T^{in}| \frac{\sum_{j=1}^{T}\frac{qj+T}{(q\alpha+T)^2}\prod_{1\le m\ne j\le T}(1-\frac{m-\alpha}{q\alpha+T}) - \sum_{j=1}^{T}\frac{qj}{(q\alpha+T)^2}\prod_{1\le m\ne j\le T}(1-\frac{m}{q\alpha+T})}{\prod_{j=1}^{T}(1-\frac{j-\alpha}{q\alpha+T}) - \prod_{j=1}^{T}(1-\frac{j}{q\alpha+T})} \\
& - \frac{q}{q\alpha+T}\sum_{i\in S_T^{in}}\left(k_i - \sum_{j=1}^{T-k_i}\frac{k_i+j}{q\alpha+T-k_i-j}\right) \\
& + \sum_{i\in S_T^{in}}(\alpha+k_i)^{-1}\left(k_i+\sum_{j=1}^{k_i}\frac{j}{\alpha+k_i-j}\right) \\
=& - \frac{|S_T^{in}|}{(q\alpha+T)^2}\frac{\prod_{j=1}^{T}(1-\frac{j-\alpha}{q\alpha+T})\sum_{j=1}^{T}(qj+T)(1-\frac{j-\alpha}{q\alpha+T})^{-1}}{\prod_{j=1}^{T}(1-\frac{j-\alpha}{q\alpha+T}) - \prod_{j=1}^{T}(1-\frac{j}{q\alpha+T})} \\
& + \frac{q|S_T^{in}|}{(q\alpha+T)^2}\frac{\prod_{j=1}^{T}(1-\frac{j}{q\alpha+T})\sum_{j=1}^{T}j(1-\frac{j}{q\alpha+T})^{-1}}{\prod_{j=1}^{T}(1-\frac{j-\alpha}{q\alpha+T}) - \prod_{j=1}^{T}(1-\frac{j}{q\alpha+T})} \\
& - \frac{q}{q\alpha+T}\sum_{i\in S_T^{in}}\left(k_i - \sum_{j=1}^{T-k_i}\frac{k_i+j}{q\alpha+T-k_i-j}\right) \\
& + \sum_{i\in S_T^{in}}(\alpha+k_i)^{-1}\left(k_i+\sum_{j=1}^{k_i}\frac{j}{\alpha+k_i-j}\right)
\end{aligned} \tag{6}
$$

$$
\begin{aligned}
\frac{\partial l(\alpha,q)}{\partial q} =& -|S_T^{in}| \frac{\sum_{j=1}^{T}\frac{\alpha(j-\alpha)}{(q\alpha+T)^2}\prod_{1\le m\ne j\le T}(1-\frac{m-\alpha}{q\alpha+T}) - \sum_{j=1}^{T}\frac{\alpha j}{(q\alpha+T)^2}\prod_{1\le m\ne j\le T}(1-\frac{m}{q\alpha+T})}{\prod_{j=1}^{T}(1-\frac{j-\alpha}{q\alpha+T}) - \prod_{j=1}^{T}(1-\frac{j}{q\alpha+T})} \\
& - \frac{q}{q\alpha+T}\sum_{i\in S_T^{in}}\left(k_i + \sum_{j=1}^{T-k_i}\frac{k_i+j}{q\alpha+T-k_i+j}\right) \\
=& - \frac{\alpha|S_T^{in}|}{(q\alpha+T)^2}\frac{\prod_{j=1}^{T}(1-\frac{j-\alpha}{q\alpha+T})\sum_{j=1}^{T}(j-\alpha)(1-\frac{j-\alpha}{q\alpha+T})^{-1}}{\prod_{j=1}^{T}(1-\frac{j-\alpha}{q\alpha+T}) - \prod_{j=1}^{T}(1-\frac{j}{q\alpha+T})} \\
& + \frac{\alpha|S_T^{in}|}{(q\alpha+T)^2}\frac{\prod_{j=1}^{T}(1-\frac{j}{q\alpha+T})\sum_{j=1}^{T}j(1-\frac{j}{q\alpha+T})^{-1}}{\prod_{j=1}^{T}(1-\frac{j-\alpha}{q\alpha+T}) - \prod_{j=1}^{T}(1-\frac{j}{q\alpha+T})} \\
& - \frac{q}{q\alpha+T}\sum_{i\in S_T^{in}}\left(k_i - \sum_{j=1}^{T-k_i}\frac{k_i+j}{q\alpha+T-k_i-j}\right)
\end{aligned} \tag{7}
$$

2 Simulation results

We simulate capture-recapture procedure to produce $d_{i(T)}$ as follows:

1. Set the true population size to N, sample size at each capture to n and number of captures to T.

2. Set the true parameters α and β.

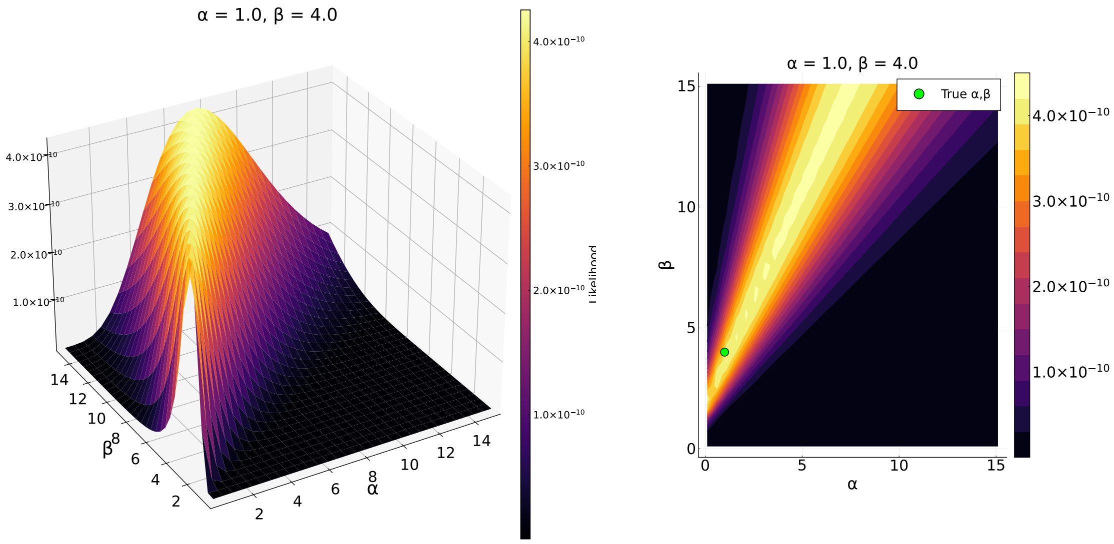

Figure 1: Likelihood function for data simulated by $\pi \sim Beta(1, 4), N = 100, n = 25, T = 2$

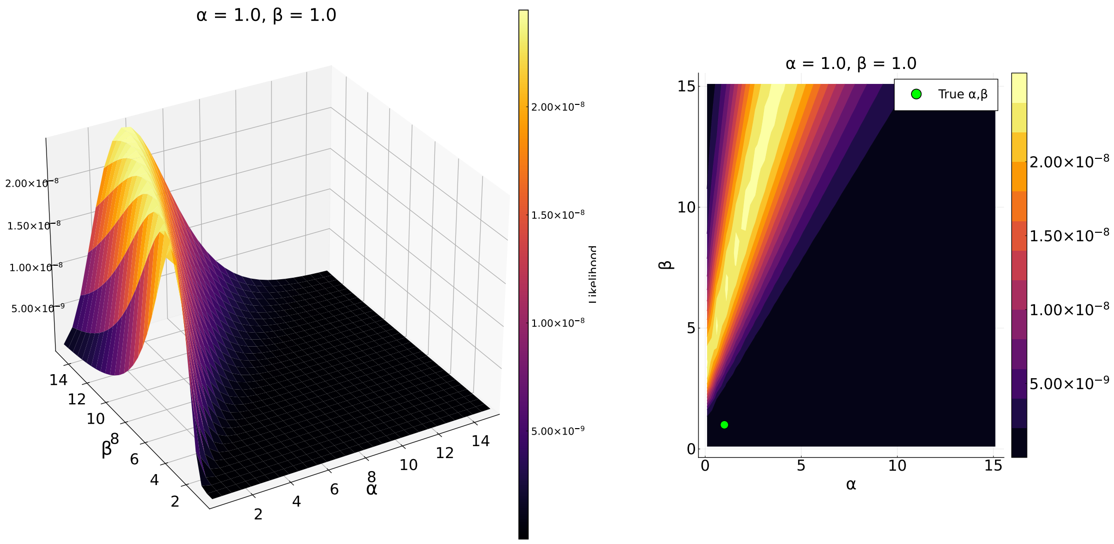

Figure 2: Likelihood function for data simulated by $\pi \sim Beta(1, 1), N = 100, n = 25, T = 2$

3. Draw N values from $\pi \sim Beta(\alpha, \beta)$.
4. Normalise π_i by dividing by the sum $\sum_{i=1}^{N} \pi_i$.
5. At each replication $t = 1, \ldots, T$:
   (a) Draw a sample of n numbers from $\{1, \ldots, N\}$. Denote with s_t.
   (b) For each $i \in s_t$, increment $d_{i(T)}$ by 1. If $d_{i(T)}$ was never recorded before set $d_{i(T)} = 1$.

Once we acquire $d_{i(T)}$, it is possible to calculate the exact likelihood using (3) multiplied by the prduct of binomial coefficients $\binom{T}{k_i}$. Figures 1-3 show surface and contour plots of the likelihood function for data simulated using different true α, β at parameter values $\{0.1, 0.6, \ldots, 15.1\}$. The population size was set to 100, two samples of size 25 were drawn.

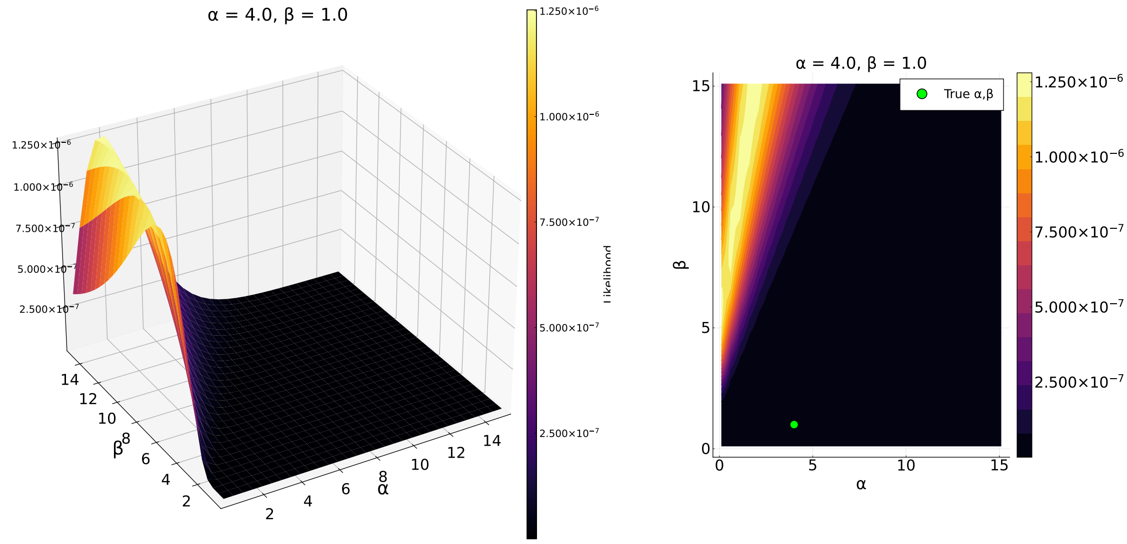

Figure 3: Likelihood function for data simulated by $\pi \sim Beta(4, 1), N = 100, n = 25, T = 2$