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Specification of informative priors for capture-recapture finite mixture models

Specificazione di a-priori informative per modelli cattura-ricattura a misture finite

Pierfrancesco Alaimo Di Loro[1], Gianmarco Caruso[2], Marco Mingione[2], Giovanna Jona Lasinio[2], Luca Tardella[2]

Abstract Many models involve binomial terms depending on parameters $p \in [0,1]$ representing probabilities. That is the case of capture-recapture experiments, where capture and survival of each individual at different occasions are modelled as Bernoulli trials with unknown probabilities. In most actual data applications, the population of interest typically exhibits unaccounted heterogeneity, presumably depending on its partitioning into a finite set of sub-populations, each one having its parameter value. If the sub-population labels are unknown, Finite Mixture Models (FMM) can be exploited to recover the unknown labels and all other model components jointly. Nevertheless, the naive application of finite mixture models within the Bayesian machinery is affected by the so-called *label-switching* problem. The group-specific parameters are assigned ordering constraints to identify their relative roles to overcome this issue. That is usually achieved by specifying conditionally uniform densities that respect such constraints, preventing the possibility to shape the prior according to available prior knowledge. In this work, we propose two flexible classes of joint priors based on manipulating Beta distributions. The idea is to specify a joint prior that retains the flexibility to induce the desired marginal behaviour while still guaranteeing the desired ordering.

Abstract *Diversi modelli includono componenti Binomiali dipendenti da parametri $p \in [0,1]$, che rappresentano probabilità. Questo è il caso di modelli cattura-ricattura, dove la cattura e la sopravvivenza di ciascun individuo in ciascuna occasione sono visti come esperimenti Bernoulliani con probabilità incognite. Nella maggior parte delle applicazioni reali, la popolazione di interesse presenta ulteriore eterogeneità, presumibilmente dovuta al partizionamento della popolazione in sottopopolazioni, ciascuna avente il proprio valore del parametro. Se le etichette della sottopopolazione sono incognite, i modelli a mistura finita possono essere usati per stimare congiuntamente le etichette e le altre componenti del modello. Tuttavia, la semplice applicazione di questi modelli in un contesto Bayesiano soffre del cosiddetto problema di label-switching. Per risolvere questo problema, i parametri gruppo-specifici vengono sottoposti a vincoli di ordinamento. Questo si ottiene tipicamente attraverso la specificazione di distribuzioni Uniformi condizionate che rispettano l'ordinamento, ma che non permettono l'elicitazione di distribuzioni a priori basate su un'eventuale conoscenza pregressa del fenomeno. In questo lavoro, si propongono due classi flessibili di distribuzioni a priori congiunte, basate sulla distribuzione Beta. L'idea è quella di specificare una a priori congiunta che mantenga una flessibilità tale da indurre marginalmente il comportamento desiderato, garantendo allo stesso tempo l'ordinamento.*

Key words: Finite mixture, Bayesian Statistics, Prior elicitation, Capture-recapture, Binomial model

1 Introduction

The implementation of capture-recapture methods in a Bayesian context often involves the specification of Beta distributions to model the prior beliefs on the capture and survival probabilities of the individuals.

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The Beta distribution is a very common candidate as a prior for such parameters p: it is compactly supported on $[0,1]$. It can be shaped to represent non-informative or informative settings by manipulating its two shape parameters. However, real data often exhibit additional heterogeneity concerning standard modelling assumptions, as not all the individuals in the population behave in the same way. For instance, the population may be partitioned into a finite set of G sub-populations, or groups, (e.g. by gender, residency pattern, size, etc.), each one having its own parameter value, say $p_g,\ g=1,\dots,G$ [McLachlan et al., 2019]. When the group labels are unknown, the partition must be estimated to get reliable inferences. In many applied sciences, the partition is often recovered in advance and subsequently passed to the model as an input [Pace et al., 2021]. Nevertheless, it is usually preferable to perform the classification and the estimation simultaneously to quantify the uncertainty of both better. In this respect, capture-recapture models can be embedded in a Finite Mixture (FMM) setting [Pledger, 2000, 2005; Böhning et al., 2005]. Each unit is uniquely assigned a latent label representing its membership to one of the G possible groups. The posterior distribution of the unknown labels is recovered jointly with all other model components, properly propagating the uncertainty of all the unknowns.

The naive application of finite mixture models within the Bayesian machinery is affected by the so-called *label-switching* problem. That is, at each Markov Chain Monte Carlo (MCMC) step, the groups may interchange their relative role [Jasra et al., 2005]. Under genuine multimodality, an effective and trivial solution is to uniquely identify the components by including prior information about their marginal and relative behaviour, as by imposing ordering constraints that define the group-specific parameters' positions in a hierarchy [Diebolt and Robert, 1994; Stephens, 2000]. When the parameters are constrained in the $[0,1]$ set, the corresponding joint prior could be derived as the product of conditionally specified uniform densities that respect such constraints. It inevitably jeopardizes the possibility of eliciting informative priors whenever the information is available. In this work, we propose two flexible classes of joint priors for this scenario, based on the manipulations of the Beta distribution. The idea is to specify a joint prior that guarantees the desired ordering constraints and retains the flexibility to include prior information in each component's marginal.

2 The modeling framework

For the sake of brevity, we here report the modelling framework, in which we included our proposals when the number of sub-populations is $G=2$. Remark that this can be easily generalized to $G>2$ cases simply by re-iterating the conditioning process.

Let $\boldsymbol{y}_1,\dots,\boldsymbol{y}_n$ be n realizations of an l-dimensional random vector with distribution $\boldsymbol{Y}\sim f(\cdot\,|\,\boldsymbol{p})$, where $\boldsymbol{p}=(p_1,p_2)$ and

$$f(\boldsymbol{y}\,|\,\boldsymbol{p})=\sum_{k=1}^{2} w_k\cdot f(\boldsymbol{y}\,|\,p_k).$$

This is a finite mixture distribution with 2 components and prior weights w_k, $k=1,2$. This setting can be more efficiently represented by augmenting the space with a latent indicator variable $\zeta\in\{1,2\}$ that denotes from which of the two densities each observation come from. The component weights w_k are the prior probabilities that each unit belongs to one group or the other $P(\zeta_i=k)=w_k$, $i=1,\dots,n$, $k=1,2,$. It represents the relative proportion of observations coming from the two groups. Bayesian inference is usually pursued through the following hierarchical specification:

$$\begin{aligned}&\boldsymbol{Y}\,|\,\boldsymbol{p},\zeta,\boldsymbol{w}\sim f(\cdot\,|\,p_\zeta)\\&\zeta\,|\,\boldsymbol{w}\sim MN_2(\boldsymbol{w}),\quad \boldsymbol{p}\sim\pi_{\boldsymbol{p}}(\cdot)\\&\boldsymbol{w}\sim Dir(\boldsymbol{\alpha}),\end{aligned}$$

where $MN_2(\cdot)$ is the two-components multinomial distribution, $Dir(\cdot)$ the Dirichlet distribution and $\pi_{\boldsymbol{p}}(\cdot)$ is the joint prior on the group specific probabilities p_1,p_2. In order to avoid the label-switching problem, the prior on $\boldsymbol{p}$ shall envision an ordering constraint to solve the symmetry in the posterior distribution and make the two components identifiable. For instance, we could enforce $p_1 < p_2$ by specifying the joint prior in a conditional fashion:

$$\pi_{\boldsymbol{p}}(p_1, p_2) = \pi_{p_1}(p_1) \cdot \pi_{p_2 \mid p_1}(p_2), \tag{1}$$

where $\pi_{p_2 \mid p_1}(\cdot)$ guarantees $p_2 > p_1$, e.g. has a support depending on p_1. When p_1 and p_2 are probabilities (i.e. $\in (0,1)$), the most striaghtforward solution is to have a Beta prior on p_1 and then specify $\pi_{p_2 \mid p_1}(\cdot) = Unif(\cdot \mid p_1, 1)$. In practice, any other specification of $\pi_{p_2 \mid p_1}(\cdot)$ complying with the ordering constraint could be valid. Nevertheless, there is very few literature that explores the marginal distribution induced on $p_2 \sim \pi_{p_2}(\cdot)$ obtained by integrating p_1 out from Eq. 1.

In Sec. 3 and Sec. 4, we investigate some alternative specifications that allow for controlling the marginal expected value and variance, and possibly also the form of the two marginals. These tools can be exploited to embed prior information in the estimation process, which can, in turn, favour the proper identification of the two components.

3 The Beta and truncated Beta

It is possible to derive the marginal prior distribution of p_2, when $p_1 \sim Beta(\alpha_1, \beta_1)$ and $p_2 | p_1 \sim tBeta(\alpha_2, \beta_2, p_1, 1)$, where $tBeta(\cdot, \cdot, l, u)$ denotes the *truncated Beta* in (l, u). However, the expression of the marginal $\pi_{p_2}(\cdot)$ is not trivial unless we set $\alpha_2 = 1$, for which we obtain:

$$\pi_{p_2}(p_2) = \frac{B(\alpha_1, \beta_1 - \beta_2)}{B(\alpha_1, \beta_1)} \beta_2 (1 - p_2)^{\beta_2 - 1} F_{Beta(\alpha_1, \beta_1 - \beta_2)}(y), \quad \text{with } \beta_1 > \beta_2.$$

In particular, when $\alpha_1 = \beta_2 = k$ and $\beta_1 = k + 1$, i.e. $p_1 \sim Beta(k, k+1)$ and $p_2 | p_1 \sim tBeta(1, k, p_1, 1)$, then we obtain the following convenient result for the marginal:

$$p_2 \sim Beta(k+1, k), \quad k > 0. \tag{2}$$

Notice that, in this particular case, the marginal distribution induced on p_2 is symmetrical with respect to the distribution of p_1 around the vertical line $p^* = 0.5$.

4 The Beta and restricted Beta

The *restricted Beta* (also called *4-parameters Beta*) is a Beta random variable which has been shifted and scaled to lie on a different domain (l, u).

In other words, if $X \sim Beta(\alpha, \beta)$ and $Z = l + X \cdot (u - l)$, then $Z \sim rBeta(\alpha, \beta, l, u)$. The expected value and variance of Z are:

$$\mathbb{E}[Z] = \frac{\alpha}{\alpha + \beta} \cdot (u - l) + l = \frac{u\alpha + l\beta}{\alpha + \beta}, \qquad \mathbb{V}[Z] = \frac{\alpha\beta}{(\alpha + \beta)^2 (\alpha + \beta + 1)} \cdot (u - l)^2$$

The restricted Beta can be exploited to specify a compelling joint prior for p_1 and p_2. If $p_1 \sim Beta(\alpha_1, \beta_1)$ and $p_2 \mid p_1 \sim rBeta(\alpha_2, \beta_2, p_1, 1)$ then the corresponding marginal expected value and variance of p_2 can be derived as a function of mean and variance of p_1 using the *Tower Law*:

$$\begin{aligned}
\mathbb{E}[p_2] &= \frac{\alpha_2}{\alpha_2 + \beta_2} + \mu_1 \frac{\beta_2}{\alpha_2 + \beta_2} \\
\mathbb{V}[p_2] &= \sigma_1^2 \cdot \frac{\beta_2^2}{(\alpha_2 + \beta_2)^2} \left(1 + \frac{\alpha_2}{\beta_2(\alpha_2 + \beta_2 + 1)}\right) + (1 - \mu_1)^2 \cdot \frac{\alpha_2 \beta_2}{(\alpha_2 + \beta_2)^2 (\alpha_2 + \beta_2 + 1)}
\end{aligned} \tag{3}$$

where $\mu_1 = \mathbb{E}[p_1]$ and $\sigma_1^2 = \mathbb{V}[p_1]$. Thus, once chosen α_1 and β_1 to comply with some prior information on μ_1 and σ_1^2, we can elicit the values of α_2 and β_2 to respect prior knowledge on μ_2 and σ_2^2 simply by solving a linear system based on Eq. (3).

5 Application in Capture-Recapture analysis

Here, we illustrate the component-specific parameters' prior specification in the context of Capture-Recapture methods.

Capture-Recapture methods are widely employed in estimating the size of elusive populations whose units are subject to multiple captures across several occasions. Here, we assume that the population of interest is *closed* and individuals belonging to the population are *captured independently* one another [Otis et al., 1978]. When this is the case, even when the sampling occurred at J on different occasions, the overall capture frequencies of each individual are sufficient to make inference on the unknown population size N.

Let y_i be the capture frequency of the i-th unit across the J occasions, for $i = 1, \dots, N$, and let D be the total number of distinct *observed* individuals (i.e. captured at least once). The unknown populations size N can range from D to infinity. Following Royle and Dorazio [2012], we can bound the parameter space of N with a large (at will) upper bound M and augment the data sample with null capture frequencies $(y_{D+1}, \dots, y_M) = (0, \dots, 0)$ (representing fake individuals) in order to exploit classical MCMC sampling in a Bayesian framework. This is achieved by introducing a collection of i.i.d. latent variables $z_1, \dots, z_M$ that indicate whether the individual i belongs ($z_i = 1$) or not ($z_i = 0$) to the true population of N individuals. It is straightforward to see that $N = \sum_{i=1}^{M} z_i$. The advantage of this kind of modelling lies in the possibility to perform Bayesian inference without the need to jump between parameter spaces of varying dimensions, and this avoids the implementation of application-specific *Reversible Jump MCMC* [King and Brooks, 2002].

In particular, a uniform prior distribution in the discrete set $\{0, \dots, M\}$ is induced on N if we consider the hierarchical specification $z_i \mid \psi \sim Bern(\psi)$, $i = 1, \dots, M$ and $\psi \sim Unif[0,1]$, where ψ is the probability that an individual of the augmented dataset of size M is a member of the true population.

With the purpose of modelling the capture heterogeneity between individuals, this framework can be embedded in a FMM setting by considering finite mixture of two binomial distributions [Pledger, 2000] for the counts y_i

$$y_i | z_i \sim w \cdot Bin(J, \, p_1 \cdot z_i) + (1 - w) \cdot Bin(J, \, p_2 \cdot z_i) \, ,$$

where w is the probability that individual i belongs to the first mixture component and p_g ($g = 1, 2$) is the capture probability of the g-th component. Notice that $y_i = 0$ almost surely when $z_i = 0$ so that the previous model corresponds to a finite mixture of zero-inflated binomial distributions.

5.1 Simulation experiment

This section shows comparative merits of alternative prior specifications in dealing with label switching and exploiting prior information on group-specific parameters. We simulated $k = 1, \dots, 50$ alternative capture-recapture datasets from closed populations with 2 groups. The simulation scheme mimics the model described in Sec. 5. Captures have been organized in $J = 10$ different occasions on a *super-population* of size $M = 500$, with a probability to be included in the actual population of $\psi = 0.3$, for all datasets. This yields an expected value of $\mathbb{E}[N_k] = 150$ across all datasets. Individuals have been allocated to the two groups evenly, setting $w = 0.5$. The group-specific capture probabilities have been set to $p_1 = 0.2$ and $p_2 = 0.4$. Under the closure hypothesis, the capture histories of each dataset have been collapsed into the vector of individual overall capture frequencies $\boldsymbol{y}_k = \left[y_1, \dots, y_{D_k}\right]$, where D_k is the number of distinct observed individuals of the simulated set k. The following five priors on the group-specific capture probabilities are considered, which correspond to those represented in the upper panels of Fig. 1:

A) $p_1 \sim Unif[0,1]$ and $p_2 \sim Unif[0,1]$;

B) $p_1 \sim Beta(1.08, 4.32)$ and $p_2 \sim Beta(3.44, 5.16)$, with hyperparameters centered on the true values $\mathbb{E}[p_1] = 0.2$ and $\mathbb{E}[p_2] = 0.4$ with $\mathbb{V}[p_1] = 0.2/10$ and $\mathbb{V}[p_2] = 0.4/10$;

C) $p_1 \sim Unif[0,1]$ and $p_2 | p_1 \sim Unif[p_1, 1]$, naive constrained prior inducing an improper marginal prior on p_2;

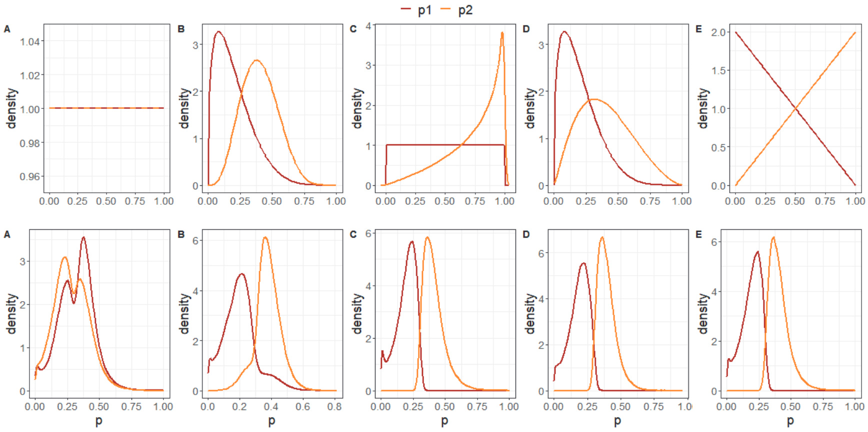

Fig. 1: Comparison between the marginal prior (*upper panels*) and posterior (*lower panels*) distributions for the parameters p_1 and p_2 for the five considered settings (A-E).

D) $p_1 \sim Beta(1.4, 5.6)$ and $p_2|p_1 \sim rBeta(0.826, 2.478, p_1, 1)$, inducing a marginal prior distributions on p_2 with the same means and variances of those considered in setting B;
E) $p_1 \sim Beta(1,2)$ and $p_2|p_1 \sim tBeta(1,1,p_1,1)$ which induces a marginal prior $p_2 \sim Beta(2,1)$ favoring repulsion between the two components.

The model in Sec. 5 is then coded and estimated in JAGS [Plummer et al., 2003] separately on each dataset and for each prior specification. Posterior samples of the capture probabilities p_1 and p_2 corresponding to different datasets have been merged (by prior setting) to analyze their overall behavior. The lower panels in Fig. 1 show their distribution, highlighting how they seem to be correctly identified whenever an ordering constraint between p_1 and p_2 is present (cfr. C-E). On the other hand, when independent priors (cfr. A-B) are considered, the posterior samples are affected by the label switching issue. Notably, regardless of the prior specifications, posterior distributions on p_1 and p_2 tend to be similar in settings C to E. Finally, the differences between the estimated posterior mean $\hat{N}_k$ and its true value N_k have been evaluated for each dataset $k = 1, \dots, 50$. The overall performances of the different prior setting have been compared in terms of *average Predictive Interval Width* (PIW), *Root Mean Squared Error* (RMSE) and *Deviance Information Criterion* (DIC). Results are reported in Table 1, which highlights how the *constrained informative* prior (i.e. setting D) provides the best performances in all indicators, shortly followed by Setting E and A. Notably, including prior information without introducing constraints to avoid the label switching issue does not yield any improvement (on the contrary it worsens the results).

	A	B	C	D	E
PIW	46	49	51	41	43
RMSE	6.7	7.1	7.5	5.9	6.3
DIC	785.6	787.8	787.7	776.9	787.8

Table 1: 95% Prediction interval width (PIW), Root Mean Squared Error (RMSE) for N, and DIC for the five considered settings (A-E).

6 Final discussion

In light of the above, we can state that constrained priors on capture probability parameters are effective in avoiding the label switching issue, as shown in Sec. 5.1. In particular, if prior information is elicited correctly, it can improve the estimation and predictive performances of the model under the condition that constraints to avoid label switching are present (setting D).

Such a proposal's effectiveness must be tested on a real data example for which the finite mixture assumption is suitable. The simulation study could then be extended to a number of groups $G > 2$ in order verify the robustness of the procedure. Eventually, the whole prior setting could be extended to the more general case where the population is open, including also entrance and survival probabilities that my be assumed to be group-specific or not.

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