A hierarchical bayesian model for modelling benthic macroinvertebrates densities in lagoons

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Abstract The ecological status classification of aquatic ecosystems requires separate quantification of natural and anthropogenic sources of environmental variability. A clustering of ecosystems into ecosystem types (i.e. Typology) is used in order to minimise natural variability. Among transitional water quality elements, benthic macroinvertebrates are the most exposed to natural variability patterns due to their life cycles and space-use behavior. Here, we address the ecological status classification issue for Mediterranean and Black Sea lagoons, using benthic macroinvertebrates, from a set of 12 reference lagoons. Two main classification approaches have been proposed in literature: the *a-priori* approach, based on standard multimetric indices, and the *a-posteriori* approach, based on linear mixed models. It may happen that different indices are in disagreement with respect to lagoon classification. We propose a Bayesian hierarchical model in which the multimetric indices are jointly modeled through a multivariate normal mixture. Each mixture component is estimated as function of covariates of interest and corresponds to an ecological status. We compare the proposed model with the *a-priori* and *a-posteriori* approaches highlighting pros and cons of each method.

Key words: Bayesian inference, classification, ecological status

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1 Introduction

The classification of ecological status of aquatic ecosystems is of interest for both biological and economic reasons. From a biological point of view, the ecological status of lagoons is strongly related to ecosystem health that is a key challenge of the scientific research. On the other hand, the knowledge of the ecological status allows a more accurate fund allocation for cleaning up the polluted lagoons and a more cautious grant allocation for tourism. In this study we focus on Eastern Mediterranean and Black Sea lagoons, which enter one geo-morphologically and functionally defined type within the Transitional Water category in the frame of the Water Framework Directive of the European Commission [3]. Benthic macroinvertebrates are known to be sensitive to different sources of abiotic heterogeneity in lagoon ecosystems, such as water salinity, sediment granulometry, composition and type of vegetation [5]. Lagoon surface area and lagoon hydrology also influence species richness and diversity in lagoon ecosystems [5]. Similarly individual body size in benthic macroinvertebrates is known to be affected by different sources of lagoon heterogeneity, such as salinity, sediment composition and lagoon surface area. Nevertheless, few attempts have been made to quantify the natural variability of benthic macroinvertebrate guilds in lagoon ecosystems.

1.1 Lagoon ecological status classification

The *a-priori* approach to lagoon classification was proposed in [2],[1] and in [3]. In these papers, the relevance of lagoon typology, season and habitat components is quantified in multimetric descriptors of the macroinvertebrate community. Multimetric metrics were *M-AMBI* [6] and *ISS* [3]. *M-AMBI* (Multivariate *AMBI*) is a multimetric index that combines the Shannon-Wiener index, the numerical density and the *AMBI* index (a taxonomically based sensitivity index) in [2] through a factorial analysis. In [1], according to reference samples, the authors fixed the boundary values that allow to classify the ecological status according to *M-AMBI*. *ISS* (index of size spectra sensitivity) proposed in [3] is a not-taxonomically based index which integrates size structure metric, size class sensitivity and taxonomic richness, the latter as a threshold correction factor. Other multimetric indices, based on similar ideas, are *BAT* and *BITS* (for a full description see [1]). The *a-posteriori* approach was proposed in [6]: the authors estimate a linear mixed model to assess the effects of some predictors, such as salinity, surface area, temperature, season, sediment granulometry and oxygen, on the multimetric descriptors *ISS*, *M-AMBI*, *BAT* and *BITS*. Four mixed models were estimated and the estimates were used to define reference values for the classification of the ecological status of lagoons. The main advantage of the approach proposed in [6] is that it allows to classify the ecological status taking into account some structural characteristics of the lagoons significantly related to multimetric descriptors. However, both approaches, *a-priori* and *a-posteriori*, have an important drawback: the same lagoon can be classified in two different ecological status according to different indices. Clearly the disagreement of the indices does not allow to appropriately classify the ecological status of the lagoons in a unique and correct way. In Section 3 we model four indices jointly, so that the classification is done according to all indices.

2 Data description

Data on benthic macroinvertebrates colonizing various habitat types were collected in 12 transitional water ecosystems located in different countries: Italy, Albania, Greece and Romania. Field sampling campaigns were performed in autumn 2004 and spring 2005 in all selected ecosystems. Sampling sites in every ecosystems were chosen so as to include a variety of habitat types and depth levels. Overall 101 sites were samples pooling the two seasons. For each sampling site, benthic samples were counted under stereomicroscope in the laboratory. Chemical and physical water parameters (water salinity, dissolved oxygen and temperature) were monitored at each station. For each lagoon, we computed simple metrics such as the numerical density, the biomass density, the taxonomic richness, the size spectra, *AMBI* and size spectra sensitivity, the Shannon and Margalef diversity indeces. Also the multimetric indices *M-AMBI*, *ISS*, *BAT* and *BITS* were computed.

3 The proposed model and results

Let $\mathbf{Y}_{ls}^T = \left(Y_{1ls}\ Y_{2ls}\ Y_{3ls}\ Y_{4ls} \right)$ be the vector of multimetric indices *ISS*, *M-AMBI*, *BAT* and *BITS* observed at lagoon l ($l = 1,...,12$) and at site s ($s = 1,..n_l$, where n_l is the number of sites of lagoon l). Let $X1_l, X2_l, X3_l, X4_l$ be respectively the values of the observed salinity, temperature, season and surface area of lagoon l averaged over the sites s. The proposed model can be written as a Bayesian hierarchical model whose hierarchy levels are defined as follows:

1.
$$\mathbf{Y}_{ls} \sim \sum_{j=1}^{4} \pi_j N_4(\mu_{lj}, \Sigma), \qquad l = 1,\ldots,12, \quad s = 1,\ldots,n_l$$

2.
$$\mu_{lj} = \beta_0 + \beta_1 X1_l + \beta_2 X2_l + \beta_3 X3_l + \beta_4 X4_l + \delta_j \qquad j = 1,\ldots,4$$

that is $\mathbf{Y}_{ls}$ is modeled as a four component multivariate normal mixture and Σ is the covariance matrix accounting for correlation between indices. Each component defines an ecological status. Prior distributions are specified for each parameter and are intended to be non informative. Since the main aim of the model is to infer lagoons ecological status a constraint reporting the ordering of classes must be added. In this work, we fix $\delta_1 = 0$ and $\delta_j < \delta_{j+1}$ so that $\mu_{lj} < \mu_{lj+1}$ with $j = 1,2,3$ and

$\delta_j \sim N(0,100)$ for $j > 1$. This constraint accounts for the natural ordering of indices. : larger values of the multimetric indices correspond to better ecological status and it helps in avoiding the label switching of mixture components. The posterior distributions of the parameters of interest cannot be obtained analytically: ad-hoc MCMC algorithms were used in order to obtain samples from the posterior distributions. The implementation is done using WinBUGS software [7]. The model is applied to the benthos data and the ecological status was then compared with those obtained in [6] and with the method in [1].

Lagoons classification is based on posterior probability of belonging to a mixture component. According to highest posterior probability, the lagoons have been classified as follows: [**Poor**] Sinoe, [**Moderate**] Agiasma, Cesine and Grado Valle Cavanata, [**Good**] Alimini, Grado Marano, Grado Valli da Pesca, Logarou, Narta and Torre Guaceto, [**High**] Karavasta and Patok. These results are coherent with ecological knowledge and with those in [6] and [1]. The main advantage of the proposed approach is that it avoids the apriori choice of benchmark values of class boundaries, providing a more objective classification tool.

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