Ecological Indicators 80 (2017) 303–315

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Assessing the role of the spatial scale in the analysis of lagoon biodiversity. A case-study on the macrobenthic fauna of the Po River Delta

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ARTICLE INFO

Keywords:
Lagoon biodiversity
Macrobenthic fauna
Tsallis entropy
Biodiversity partitioning
Mixed effects models

ABSTRACT

The analysis of benthic assemblages is a valuable tool to describe the ecological status of transitional water ecosystems, but species are extremely sensitive and respond to both microhabitat and seasonal differences. The identification of changes in the composition of the macrobenthic community in specific microhabitats can then be used as an "early warning" for environmental changes which may affect the economic and ecological importance of lagoons, through their provision of Ecosystem Services. From a conservational point of view, the appropriate definition of the spatial aggregation level of microhabitats or local communities is of crucial importance. The main objective of this work is to assess the role of the spatial scale in the analysis of lagoon biodiversity. First, we analyze the variation in the sample coverage for alternative aggregations of the monitoring stations in three lagoons of the Po River Delta. Then, we analyze the variation of a class of entropy indices by mixed effects models, properly accounting for the fixed effects of biotic and abiotic factors and random effects ruled by nested sources of variability corresponding to alternative definitions of local communities. Finally, we address biodiversity partitioning by a generalized diversity measure, namely the Tsallis entropy, and for alternative definitions of the local communities. The main results obtained by the proposed statistical protocol are presented, discussed and framed in the ecological context.

1. Introduction

Transitional waters, such as coastal areas, are highly heterogeneous ecosystems in relation to the high variation of chemical, physical, morphological, hydrodynamic and/or functional factors (Basset et al., 2013). These systems are characterized by high instability (Sousa et al., 2009) which is associated to the instability of their fresh water sources (e.g. floods, droughts of rivers/streams and sediment transport) and to the sea tide. In recent years, phenological shifts have been observed in the vegetation of these ecosystems in strictly aquatic areas (Viaroli et al., 2001), with the disappearance of rooted macrophytes (e. g. *Zoostera* and *Ruppia*) replaced by phytoplankton and macroalgae ephemeral (e.g. *Ulva*) (Raffaelli et al., 1998), and in limiting areas (shore and shallow waters), with the marked decrease or disappearance of *Phragmites* that were previously abundant in the riparian zones of European coastal areas with relatively low salinity (Van der Putten, 1997; Fogli et al., 2002). These changes are associated to the increase of anthropogenic activities over the coastal areas such as fishing (fish, mussels and clams), sand abstraction, agricultural pollution by nutrients causing eutrophication (Viaroli et al., 2001), etc. Thus, modification of the aquatic vegetation is expected to change the whole community and therefore the ecosystem functionality and provided ecosystem services (Eyre and Ferguson, 2002; Smith 2003; Newton et al., 2014). The aforementioned aspects indicate the need to increase our knowledge on transitional areas' functioning in order to improve the development of biodiversity conservation plans. Legislation and actions have been adopted to stop further deterioration and restore these areas to a healthy state. The Water Framework Directive (WFD, 2000/60/EC) requires EU Member States to assess the ecological status of each water body in Europe and to ensure a sustainable management such that good ecological quality of all water bodies would be obtained by 2015. The analysis of benthic assemblages is a valuable tool to describe the ecological status of these transitional ecosystems, since macrobenthic fauna is known to be highly correlated with the sediment, which accumulates the multiple sources of organic enrichment and pollution (Pearson and Rosenberg, 1978). Macrobenthic species are extremely sensitive and respond to both microhabitat and seasonal differences, adding complexity to the variability of these ecosystems

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http://dx.doi.org/10.1016/j.ecolind.2017.05.037
Received 20 March 2017; Received in revised form 12 May 2017; Accepted 12 May 2017

(Carvalho et al., 2011). Consequently, the importance of habitat definition has often been highlighted in connection with lagoon ecological status assessment (Gamito et al., 2012).

The identification of changes in the composition of the macrobenthic community in specific microhabitats can be used as an “early warning” for environmental changes which may affect the economic importance of lagoons, through their provision of ecosystem services (e.g. nutrient cycling, flood control, shoreline stabilization, water quality improvement, fisheries resources, habitat and food for migratory and resident animals and recreational areas for humans) (Basset et al., 2013; Pinna et al., 2013). Understanding assemblage responses to the environmental gradients at multiple spatial scales is an important issue in conservation biology (Bae et al., 2014). From a conservational point of view, several questions arise. What is the importance of the biodiversity of a single microhabitat with respect to the entire ecosystem? Which microhabitats contribute more to the entire ecosystem biodiversity? Is it possible to maintain biodiversity of the entire lagoon preserving only the most diverse microhabitats or should we care more about the conservation of ecosystem peculiarities? Should we consider a lagoon as a combination of microhabitats? All these questions address the same fundamental issue, i.e. the appropriate definition of the spatial aggregation level of microhabitats or local communities (monitoring station, microhabitat, area, lagoon). A major focus of interest in Ecology has to do with understanding changes in patterns of diversity for spatial scales ranging from the local community to the entire ecosystem. Defining the local community corresponds to setting the spatial scale for the interactions between organisms and their environment. The partition between local and regional scales is an artificial idealization for a more complex reality. For most ecosystems there is a nested hierarchy of multiple spatial scales characterized by different biological processes (Loreau, 2000; Whittaker, 1977). The pressures affecting biodiversity patterns are often scale specific, making multiscale assessment a crucial methodological priority. As species richness is not additive, it is difficult to translate from the scale of measurement to the scale(s) of interest.

A number of methods have been proposed to tackle this problem, but some of them are too model specific to allow general application (Azaele et al., 2015): Brose et al. (2003) use simulated landscapes to examine the sensitivity of the bias and accuracy of different species richness estimators to spatial autocorrelation and strength of environmental gradients (among other things). Büchi et al. (2009) use a population-based model to simulate competing species in spatially explicit landscapes, investigating the influence of the spatial structure in habitat and disturbance regimes. Communities are here characterized by species richness and life-history traits. On the side of more widely applicable methods, Suurkuukka et al. (2012) use multiplicative partitioning of true diversities to identify the most important scale(s) of variation of benthic macroinvertebrate communities across several spatial hierarchical scales. Azaele et al. (2015) introduce the spatial pair correlation function (PCF) to describe the spatial structure of species' abundances. PCF describes the correlation in species' abundances between pairs of samples as a function of the distance between them. Rajala and Illian (2012) introduce a family of spatial biodiversity measures by flexibly defining the notion of the individuals' neighbourhood describing proximity of locations within the framework of graphs associated to a spatial point pattern.

The main objective of this work is to assess the role of the spatial scale in the analysis of lagoon biodiversity, the focus being on one ecosystem and a relatively small geographical scale. We first analyze the variation in the sample coverage for alternative aggregations of monitoring stations in three lagoons of the Po River Delta. Then, we analyze the variation of a class of entropy indices by mixed effects models properly accounting for the fixed effects of biotic and abiotic factors and random effects ruled by nested sources of variability corresponding to alternative definitions of local communities. Finally, we address biodiversity partitioning by a generalized diversity measure, namely the Tsallis entropy, and for alternative definitions of the local communities.

The workflow of the paper is displayed in Fig. 1. In Section 2 some technical details are given on the sampling procedures, statistical methods and mathematical ideas applied in this work. In Section 3 results are described and finally a discussion is provided in section 4.

2. Materials and methods

2.1. Study area

The study area is composed by three lagoons, all connected to the Po River Delta in Northern Italy and influenced by the Adriatic Sea. The Goro lagoon is a shallow-water embayment of the Po River Delta (44.78–44.83°N, 2.25–12.33°E), approximately triangular in shape with a surface area of 26 Km^2, an average depth of 1.5 m, and it is connected to the Adriatic Sea by two mouths about 0.9 Km wide each. The western area (Valle Giralda) is mainly influenced by freshwater inflow from the Po di Volano, while the northern part (Taglio della Falce) is influenced by both freshwater and brackish water. The central area (Valle di Goro) is mainly influenced by sea water. The eastern area (Valle di Gorino) is very shallow (maximum depth 1 m) and accounts for one half of the total surface area and one quarter of the water volume. The most southern part of the Goro lagoon is named Valle di Goro scanno, it is the closest to the open sea and bordered by sand dunes (further information in Viaroli et al. http://www.dsa.unipr.it/lagunet/infosheet/02-goro.pdf). The Comacchio lagoon, the largest lagoonal ecosystem in the Po River Delta, is located in the coastal area of the north-western Adriatic Sea, about 40 km south of Ferrara. The Valli di Comacchio is a semi-enclosed lagoonal complex of about 115 km^2, with an average depth of 1 m (0,5–1,5 m), almost completely surrounded by earthen dikes, and separated from the sea by the highly anthropogenically impacted, 2.5-km wide Spina spit. This lagoonal system is connected with the Adriatic Sea by three marine channels, the Porto Canale, Logonovo, and Gobbino, but since the latter is impounded, exchange of the Valli occurs only through the Porto Canale and Logonovo channels. Both channels enter the lagoonal complex through Valle Fattibello, which also receives a small amount of water through the Navigable channel, and then flow into the northern basin of Valle Magnavacca. The complex of Comacchio includes six basins, five of them are considered in this study: Valle Magnavacca (about 62 km^2), Valle Campo (about 30 km^2), Valle Smarlacca (about 2 km^2), Valle Fattibello (about 8 km^2) and Valle Spavola (about 2 km2). Valle Fattibello and Valle Spavola, are separated from the others and have been considered as a lagoon by themselves named Fattibello. The bottoms of the Valli are typically muddy characterized by bare sediment (Valle Spavola and Valle Campo), or sparsely vegetated meadows of the seagrass *Ruppia cirrhosa* (Valle Magnavacca) or characterized by the presence of the green macroalgae *Ulva rigida* C. Ag. (Valle Fattibello). (Lagunet site: http://www.dsa.unipr.it/lagunet/infosheet/03-comacchio.pdf). Valle Smarlacca is located in the southeast corner of the Comacchio lagoon, close to the Reno River. It has a mean water depth of 0.8 m and the superficial sediment is mainly composed of organically enriched silts. This organic layer is 10–20 cm thick and overlies a deeper clay layer. The aquatic phanerogam *Ruppia cirrhosa* forms large patchy meadow, alternating between areas of dense canopy and areas devoid of plants. Salinity is relatively stable (22–24 psu) but can rise to 25–30 psu in summer due to evaporation. The area is surrounded by embankments and is completely separated from the other basins of the Comacchio lagoon. Valle Smarlacca receives freshwater and nutrient inputs from the adjacent Reno River through artificially-regulated sluices. The Valle Smarlacca area is also exploited for fish farming (Lagunet site: http://www.dsa.unipr.it/lagunet/infosheet/04-smarlacca.pdf).