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Selection of ecological indicators for the conservation, management and monitoring of Mediterranean coastal salinas

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Abstract Salinas systems are artificial wetlands which are interesting from the viewpoint of nature conservation. They play an important role both as habitats for migratory waterbird species and as nodes of biotic connectivity networks. In the Mediterranean basin, where the coastal salinas are highly significant as alternative and complementary habitats for waterbirds, a process of abandonment occurs, and many seminatural systems of this kind are disappearing. This abandonment is having serious consequences for migratory bird populations and for the ecological role these play. In the present paper, this group of waterbird species has been used to evaluate these wetlands for conservation purposes. We have developed a methodological approach for the selection of ecological indicators for the conservation and management of these Mediterranean habitats and waterbird assemblages, the main consumers therein. The stepwise procedure developed constitutes a practical tool for this task. Application thereof enabled us to differentiate the habitats available for the waterbirds and to identify the biotic and abiotic indicators for the maintenance and management of the salina ecosystems. These variables can then be incorporated into monitoring programs.

Keywords Ecological indicators · Habitat identification · Monitoring program · Salinas management · Systematic conservation planning

Introduction

Coastal salinas are anthropogenic supratidal habitats exploited for sea salt, which becomes progressively concentrated by evaporation. The salinas have been regulated by human activity for millennia, and structurally, they comprise a series of interconnected shallow hypersaline ponds. The flow of water through these ponds creates a steep and stable gradient of physicochemical characteristics, mainly salinity (Baudin 1980; Britton and Johnson 1987; Javor 1989). The spatial organization of the ponds in the salinas and of their different depths, necessary for the salt production process, favors a high degree of spatial heterogeneity and very productive microenvironments that are attractive to many primary and secondary consumers (Evagelopoulos et al. 2008; Hamdi et al. 2008). Such conditions are tolerated by aquatic communities with complex cycles and interspecific relationships and by species which

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are highly specialized for life in this environment (Geddes et al. 1981; Williams 1993; Forbes and Cyrus 1993; Marín and d'Ayala 1996). Fish, mollusks, and annelids are characteristic of the less saline ponds, whereas crustaceans such as *Artemia salina* thrive in places with high salt concentrations (Masero et al. 1999; López et al. 2004). Species richness generally decreases with higher salinity levels, which also very much reduce the presence of aquatic invertebrates and alter waterbird communities, the main consumers and the components most vulnerable to changes in water conditions (Kingsford and Porter 1994; Bennun 2000; Halse et al. 2002).

Throughout the world, determined waterbirds use salinas as places of rest and for feeding and breeding (Martin and Randall 1987; Myers et al. 1987; Velasquez and Hockey 1991; Batty 1992; Collazo et al. 1995; Warnock and Takekawa 1995; Timms 1997; Carmona and Danemann 1998; Sadoul et al. 1998; Castro et al. 2000). This guild of species is the one most frequently considered with regard to appraising the natural value of these wetlands for conservation as protected areas. The abundance, presence, or absence of birds have proven to be effective indicators of biological integrity in wetlands and are also considered to be good indicators of a site's ecological condition and of environmental changes therein (Bradford et al. 1998; Howe et al. 2007).

In the Mediterranean basin, many seminatural environments of this type were part of valuable coastal cultural landscapes. At present, apart from their ecological value and high biodiversity, they are valued due to becoming increasingly scarce (Britton and Johnson 1987; Sadoul et al. 1998; Castro et al. 2000; Masero et al. 2000; Aznar et al. 2002; Masero 2003; Ortega et al. 2004). Indeed, these systems have been under serious threat for the last few years, due to total or partial abandonment, resulting from diminished profitability and to development of competing land uses, such as housing, tourism, industry, etc. (Weber et al. 1999; Masero 2003; Ortega et al. 2004). Thus, in the last 50 years, over 57% of the 70,000 ha of salinas existing in the Mediterranean Basin has been lost.

The geographic location of the Mediterranean salinas also makes them a stepping stone for thousands of waterbirds during migration from their nesting places in Central and Northern Europe to wintering places in Central and Southern Africa. Their ecological function transcends their boundaries and affects an important global network of wetland systems, which should be understood and managed jointly (López et al. 2004). Thus, these manmade wetlands are also of great interest due to the functional role they play in ecological connectivity (Masero et al. 1999; Amezaga et al. 2002; Lurz et al. 2002).

Conservation and management of these systems call for the development of integrated methods aimed at understanding and assessing habitats and at defining and selecting ecological indicators related to species composition and diversity (Possingham et al. 2001; Stein and Ambrose 1998; Ortega et al. 2004). Ecological indicators can, in fact, facilitate an adaptive management approach, but only if acceptable levels for these indicators have been previously defined in order for the data collected to be interpreted (Smyth et al. 2007).

Numerous statistical techniques have been applied in order to define ecological indicators in different ecosystems (Kremen 1992; Carleton et al. 1996; Dufrene and Legendre 1997; Murtaugh and Pooler 2006). There is, however, a need for robust procedures for selecting ecological indicators in threatened ecosystems such as the Mediterranean salinas. The need to develop and improve methods and tools for controlling and preserving this type of wetlands is a priority objective for managers, decision makers, and land users. This article proposes a stepwise multivariate method for selecting ecological indicators which considers the measurable biotic and abiotic characteristics of the system (Niemi and McDonald 2004) for conservation, management, and monitoring.

Study area

The Cabo de Gata salinas are located in the Cabo de Gata-Níjar Natural Park (Southeastern Spain; Fig. 1). Salt has been produced in this area since the first century BC (Alonso et al. 2004). The climate is a sub-desertic one, with the lowest rainfall on the Iberian Peninsula (<200 mm/year). The salinas system occupies an area of ca. 300 ha

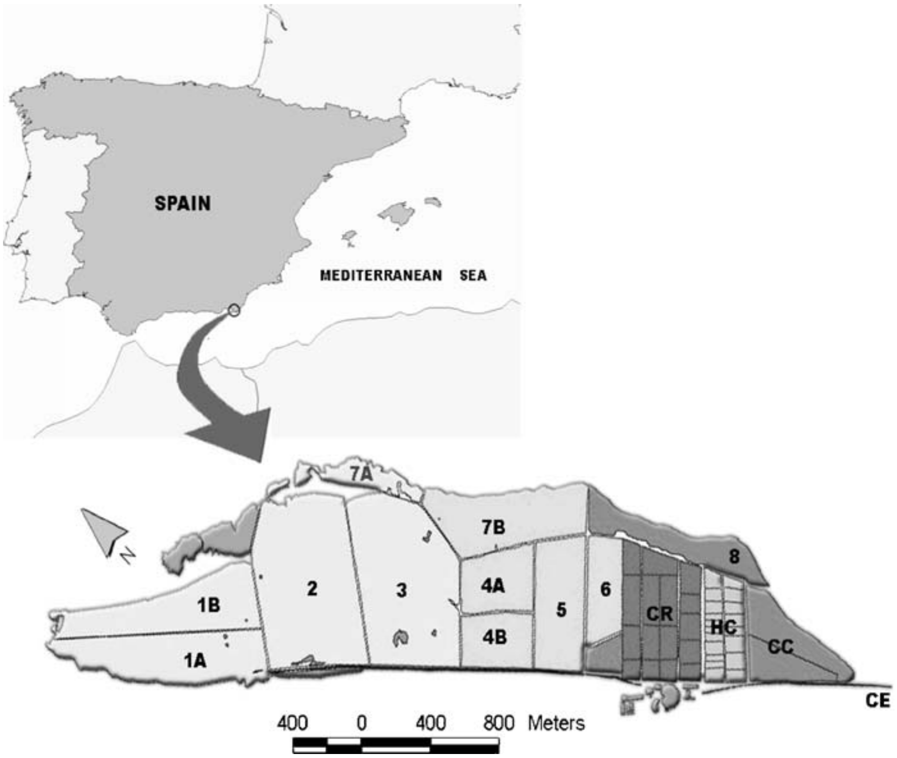

Fig. 1 Location of the Cabo de Gata salinas. Differentiation of the various types of ponds: *CE*, seawater entry channel; evaporating ponds 1*A*, 1*B*, 2,3, and 7*A*; warming ponds 4*A*, 4*B*, 7*B*, 5, and 6; concentrating ponds 8 and *CC*; final concentration ponds (*HD*) and crystallization ponds (*CR*)

along a 4,500-m long strip running parallel to the coastline, overlying flat Quaternary deposits. Their elevation below sea level and location facilitate the direct entry of seawater, channeled by gravity and by the prevailing westerly winds. These features and geographic position make it an important element on African–European bird migration routes. This system is classified as a Wetland of International Importance by the Ramsar Convention (1971), Biosphere Reserve (UNESCO-MaB 1974) and as a Special Protection Area for Birds, in accordance with the Birds Directive (1979) on the conservation of wild birds within the European Union.

The complexity of water circuit for the production of common salt in salinas involves the establishment of important ecological interactions. This complexity depends upon the size and topography of each salina (López et al. 2004). A gradient of increasing salinity, determined by the entry of seawater (Fig. 1), is set up across the various ponds of the salina. Seawater enters via a channel, CE, and discharges into the first two ponds, 1A and 1B. From these, the water flows by gravity into ponds 2, 3, and 7A by means of various sluices left open for this purpose. This preliminary group of ponds (“evaporating ponds”) receives seawater with a salinity of 37‰ and concentrates it to 67‰. The water passes to ponds 4A, 4B, and from these to 7B, 5, and 6. In this second group (“warming ponds”), salinity rises from 76‰ (in the former ones) to 128‰ (in the latter). The water then flows from warming ponds 6 or 7B into the “concentration ponds,” 8 and CC, where salinity ranges from 138‰ to 184‰. Precipitation of calcium sulfate is evident in these ponds. Finally, the water flows into the final concentrator compartments (HC), where salinity is between 184‰ and 259‰, and all the remaining sulfate precipitates out. The last group comprises the “crystallization ponds” (CR), where sodium chloride precipitates out and is subsequently harvested.

Method

Selection of baseline sites of ecological conditions

Determination of the reference ecosystem conditions is generally based upon observations and measurements made in locations that represent a certain status or condition class of ecological integrity (Angradi et al. 2009). These reference conditions are usually defined as minimally disturbed or least disturbed (i.e., little evidence of human disturbance or systems with the best extant physical, chemical, and biological habitat conditions in the current human-dominated landscape; Stoddard et al. 2006). Reference sites are usually selected by means of screening criteria based on stressor response information and expert judgment, which are used to obtain threshold values that enable different condition classes of the system to be characterized (Karr and Chu 1999; Bailey et al. 2004; Angradi et al. 2009). The reference systems selected for the present paper were littoral wetlands on the coasts of Southern Spain where the study area is located. These wetlands present a range of variability of ecological conditions and have been studied for many years, and much is, therefore, known of their ecological status, which is linked to either the natural or the anthropogenic environment. They are usually used as wintering, breeding, and feeding sites by a large number of waterbirds. Thus, the quality of different feeding habitats for birds and species distribution patterns are well known (Matamala 1986; Paracuellos et al. 1994; Gomez Mercado and Paracuellos 1995; Masero et al. 1999, 2000; Castro et al. 2000; Lopez 2001; Lopez et al. 2001; Ortega et al. 2000, 2001, 2004; Casas et al. 2003; Masero 2003; Paracuellos and Ortega 2003; Paracuellos and Telleria 2004).

Choice of the variables sampled and validation as potential ecological indicators

Selection of the variables sampled was based upon information obtained in a previous experimental study that lasted several years and was conducted in the Cabo de Gata salinas (Castro 1993; López et al. 1996; Castro et al. 2000; Paracuellos et al. 2002). It allowed the space–time composition and organization of the assemblages of birds in the studied salina to be established in detail in relation either to the environmental variability (spatial segregation of the avifauna of the salinas conditioned by the variation of the physical and chemical characteristics) or to the composition of the birds' diet. Considering that the present study refers to field conditions, we selected the variables that met the requirements to be considered as effective ecological indicators (Murtaugh 1996; Dale and Beyeler 2001): they are easily measured; they have a known response to natural disturbances, anthropogenic stresses, and changes over time; they are sensitive to stresses in studied system (salinity) and they respond to stress in a predictable manner (they present significantly different responses along the studied gradient); they predict changes that can be averted by management actions; and they have low variability in response.

As "total response variability," we considered the natural variation, which includes influences of stressors and measurement errors (Jackson et al. 2000). Quantifying the measurement error is vital in order to determine whether a variable meets the requirements to be considered as an indicator and to be used in monitoring programs. In this study, the evaluation of measurement error was developed using data collected over 4 years of sampling; we checked that the across-year variance was relatively small compared to within-year variance and that, therefore, trend detection was possible (Kurtz et al. 2001). In all cases, the measurement errors calculated were minimal due to standardized methods employed.

Sampling of physicochemical characteristics

Monthly water samples were taken over an annual cycle from twelve ponds: 1A, 1B, 2, 3, 4A, 4B, 5, 6, 7A, 7B, 8, and CC (ponds 8 and CC were dry for several months). A total of 122 samples were taken. Dissolved oxygen, pH, conductivity, temperature (between 11.00 A.M. and 12.00 A.M.), chloride, sulfate, bicarbonate, nitrite, nitrate, phosphate, sodium, potassium, calcium, and magnesium were determined according to the methods described in Clesceri et al. (1998). Calculation of total dissolved solids (TDS) was based on these analyses.

The following parameters were also measured on a monthly basis for each pond: surface area (SE), area of beach around the perimeter (SP), perimeter (Pr), mean proportion of flooded area (PMI), ratio of area/perimeter (RSP), and depth of the water column (P). The hardness of the pond bed (Pn) was determined using a Fijkelkamp penetrometer (0.5–4.5 kg/cm^2).

Sampling of macroinvertebrates and fish

As water samples were taken, benthic and pelagic samples were collected from the different types of ponds for invertebrate analysis. Pelagic samples were taken with a zooplankton net (150-µm mesh) and benthic samples by means of cores (depth 2–5 cm). Each sample consisted of five replicates (40 l filtered for each replicate of the pelagic samples). The macroinvertebrate samples were washed through a 0.5-mm mesh sieve and preserved in 5% formalin.

We counted the number of individuals and determined biomass by drying these samples (85°C over 24 h) and then weighing them.

Fish were captured using cylindrical 50 × 25-cm pots with a 4-cm diameter mouth.

Appendix provides details of the macroinvertebrates and fish (*Blenius pavo*) found.

Bird census

The abundance of 27 species of birds (Appendix) was observed monthly in each of the 12 ponds, between 6.00 A.M. and 12.00 A.M., over 3 days during the first week of each month. We recorded the number of individuals for the census of each species over these 3 days. Bird species were recorded by direct observation of individuals (Berthold 1976) with the use of a 20–60× land telescope.

Numerical analysis

1. The sampling data obtained were entered into three data matrices, each consisting of 122 observations with different numbers of variables. The first matrix [1] contained abundance data for 27 bird species over 122 observations, the second [2] contained biomass data for 15 invertebrate species and one fish species over 122 observations; and the third [3] contained data for 22 abiotic variables over 122 observations.
2. We calculated macroinvertebrate diversity and waterbird diversity using the Shannon–Wiener index (Shannon and Weaver 1949), for the salinas as a whole and for the evaporating, warming, and concentration ponds considered separately. These variables constituted a part of subsequent numerical analyses.
3. Canonical correspondence analyses (CCA; Ter Braak 1986, 1988; Ter Braak and Verdonschot 1995) were performed using normalized data. This ordination analysis is particularly appropriate in cases where the variables tend to give unimodal responses. The technique is essentially a constrained reciprocal averaging ordination. It is a hybrid of ordination and multiple regression used for detecting the principal sources of variation in the data series (Ter Braak 1995; McGarigal et al. 2000). Previous to this analysis, the Monte Carlo test (Hammersley and Handscomb 1964; Hope 1968; Olden et al. 2004), based on permutation of residual values, was employed to select the most significant variables ($p < 0.05$) in order to reduce the effects of possible collinearity between variables and to eliminate variables from the analysis that might introduce redundancy into the results.

We performed a CCA to determine, firstly, the relationship between birds and "trophic resources" using matrices [1] and [2], and secondly, the relationship between birds and their abiotic environment, using matrices [1] and [3]. We subjected the variables included in these two CCAs to a Monte Carlo analysis, which enabled us to select 14 trophic and physicochemical characteristics. Thus, we constructed a new matrix [4], which was called "resource availability," consisting of 14 variables ×122 observations. We then undertook further CCA using matrices [1] and [4].

Results

Diversity of macroinvertebrate community

Table 1 shows the diversity values calculated for the macroinvertebrate assemblage in the salinas

Table 1 Diversity values—H_i' (bits)—calculated for the macroinvertebrate assemblage in the salinas and specifically in the evaporating, warming and concentration ponds

	Salinas system	Evaporating ponds	Warming ponds	Concentrating ponds
Maximum value	1.7	1.7	0.4	2.3
Minimum value	0.6	0.4	0.0	0.0
Mean value	1.0	1.1	0.2	1.1

as a whole and for the groups of ponds taken separately (evaporating, warming, and concentration ponds). Dominance of certain species typifies each group of ponds, indicating a very low diversity. *Hydrobia acuta* and *Baeotendipes noctivaga* are both very abundant. Diversity in the salinas over the entire study period was less than 1.7 bits. In the evaporating ponds, where both species are present, the maximum value was 1.7 bits during September. The warming ponds, where there is an overriding dominance of *B. noctivaga,* show a maximum value of 0.4 bits during April. In the concentration ponds, where the macroinvertebrate community was not particularly rich, a moderate value of 2.3 bits appears during August.

Relationship between the waterbird assemblages and the habitat and trophic resources

Figure 2 and Table 2 show the results of the CCA. These allow the abundance of birds to be

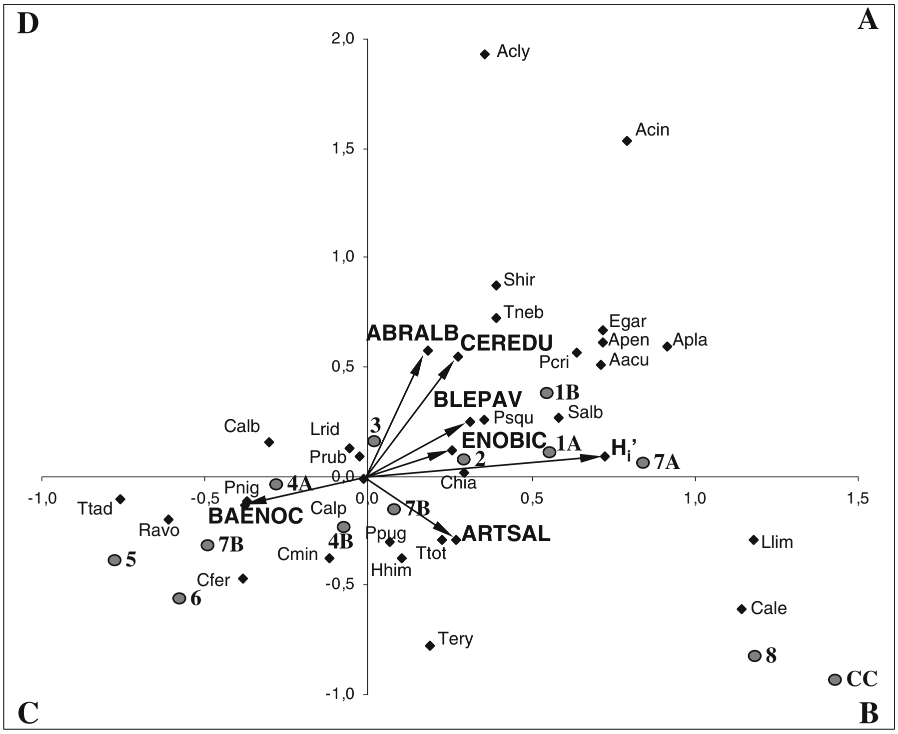

Fig. 2 Distribution of waterbird, macroinvertebrate, and fish species (selected using the Monte Carlo test) on the ordination plane of the CCA (first axis variance absorption 39.8%; second axis 26.5%). The variables previously selected by the Monte Carlo test are shown in *bold*: five macroinvertebrate species, macroinvertebrate diversity (H_i') and one fish species. We identified four habitats, which are characterized by the diversity of trophic resources and the salinity of the environment: *A* (saline habitat with diversity of trophic resources), *B* (hypersaline habitat with diversity of trophic resources), *C* (hypersaline habitat with low diversity of trophic resources), *D* (saline habitat with low diversity of trophic resources). *Gray dots* indicate the coordinates of the centroids of sampled pond groups in the ordination plane. The abbreviations of the biotic variables are shown in Appendix

Table 2 Relationships between waterbird species and "trophic habitats" characterized by macroinvertebrate diversity (H'_i), five species of macroinvertebrates and one fish species, selected using the Monte Carlo test

Variables	Variance explained by the variables (%)	Correlations between variables and canonical axes	
		Axis I	Axis II
H'_i	20.0	0.72**	0.08
A. alba	12.72	0.18	0.57**
C. edule	6.36	0.27	0.55**
A. salina	5.45	0.27	−0.29 **
E. bicolor	4.54	0.25*	0.12
B. pavo	4.54	0.30**	0.25
B. noctivaga	2.72	−0.37 **	−0.13

The variance explained (%) by each of the variables selected is shown along with their value of correlation with the first two principal axes of the CCA (Axis I 39.8% of variance absorption; Axis II 26.5% of variance absorption)

$^{*}p < 0.01$, $^{**}p < 0.005$

related to descriptors of the habitat studied. The variables selected by means of the Monte Carlo test over the set of ponds of the salina were the fish *B. pavo*, five invertebrate species (*Abra alba*, *Cerastoderma edule*, *A. salina*, *Enochrus bicolour*, and *B. noctivaga*) and macroinvertebrate diversity (H'_i).

The first axis shows a significant positive correlation with macroinvertebrate diversity and abundance of *E. bicolor* and *B. pavo* and a negative correlation with *B. noctivaga* (Table 2). This axis represents a gradient of richness and diversity of trophic resources, ranging from varied habitats to low diversity habitats dominated by *B. noctivaga*.

The positive semi-axis of the second trend is significantly correlated with *A. alba* and *C. edule*, and the negative one is significantly correlated with *A. salina*. Distribution of the macroinvertebrates along this second axis reflects a gradient of salinity ranging from environments whose conditions favor stenohaline especies (the mollusks *A. alba* and *C. edule*) to environments with euryhaline conditions (the philopod *A. salina*).

The trends indicated by the first two axes show the salinas system under study as a set of four habitats which coincide with the four quadrants of the ordination plane. Each can be defined by considering the diversity of trophic resources and the salinity of the water: saline and diverse habitat (A), hypersaline and diverse habitat (B), hypersaline and low-diversity habitat (C), and saline and low-diversity habitat (D). The birds of the extremes of the trends are clearly specialists, while those in the middle of the plane can be considered to be generalists. The aquatic birds tend to occupy the first three habitats described. The saline habitat with low-diversity trophic resources (habitat D) is not characterized by any particular species of waterbird, supporting the generalists found throughout all the environments—the sanderling (*Calidris alba*), the dunlin (*Calidris alpine)*, the black-headed gull (*Larus ridibundus*), and the greater flamingo (*Phoenicopterus rubber*).

The group of birds comprising species such as the northern shoveler (*Anas clypeata*), the eurasian wigan (*Anas penelope*), the mallard (*Anas plathyrhynchos*), the northern pintail (*Anas acuta*),the gray heron*(Ardea cinerea*), the great ringed plover (*Charadrius hiaticula*), the common tern (*Sterna hirundo*), the little tern (*Sterna albifrons*), the common greenshank (*Tringa nebularia*), the little egret (*Egretta garcetta*), the great crested grebe (*Podiceps cristatus*), and the gray plover (*Pluvialis squatarola*) is representative of saline habitats with diverse macroinvertebrate resources (habitat A). This habitat type is found in the evaporating ponds (1A, 1B, 2, 3, and 7A), which have permanent water cover and are comparatively deep (35 cm over the study period); they have a soft bed and a long perimeter and their beaches are typically populated with birds.

The waterbird group consisting of the ruff (*Philomachus pugnax*), the black-winged stilt (*Himantopus himantopus*), the common redshank (*T. totanus*), the spotted redshank (*Tringa erythropus*),the black-tailed godwit (*Limosa limosa*), and the kentish plover (*Charadrius alexandrinus*) belong to the hypersaline environments supporting a diverse macroinvertebrate community (habitat B). These characteristics correspond to the last of the warming ponds (7B) and to the concentration ponds (8 and CC), where the most representative food species is the invertebrate *A. salina*. The habitat typically has a very shallow water column (between 6 and 18 cm), a very hard bed and abundant perimeter beaches. Typical of this habitat are the small-to medium-sized insectivorous limicolous birds.

The hypersaline habitat supporting a low variety of food resources (habitat C, dominated by the dipteran *B. noctivaga*) corresponds to the group of birds consisting of the black-necked grebe (*Podiceps nigricollis*), the little stint (*Calidris minuta*), the curlew sandpiper (*Calidris ferruginea*), the avocet (*Recurvirostra avosetta*), and the common shelduck (*Tadorna tadorna*). This habitat occurs in the warming ponds (4A, 4B, 7B, 5, and 6), where mean water depth is 24 cm and where beaches are scarce.

Relationship between waterbird assemblage and abiotic environment

Figure 3 and Table 3 show the abiotic variables previously selected with the Monte Carlo test: pH, depth of the water column, dissolved oxygen content, lagoon perimeter, total dissolved solids, substrate hardness, and ratio of area to perimeter of the ponds.

The first canonical axis indicates an environmental gradient opposing hardness of the bed (positive semi-axis) against water depth (negative one): the deeper evaporating ponds have a softer substrate than the shallower concentrating ponds. Total dissolved solids and hardness of the substrate form a secondary environmental gradient in the salinas showed by the second canonical axis. The gradual increase in water salinity is directly related to the increasing hardness of the lagoon bed. In contrast, the less saline ponds have softer beds, are deeper, and have a longer perimeter; their surface area/perimeter ratio is greater,

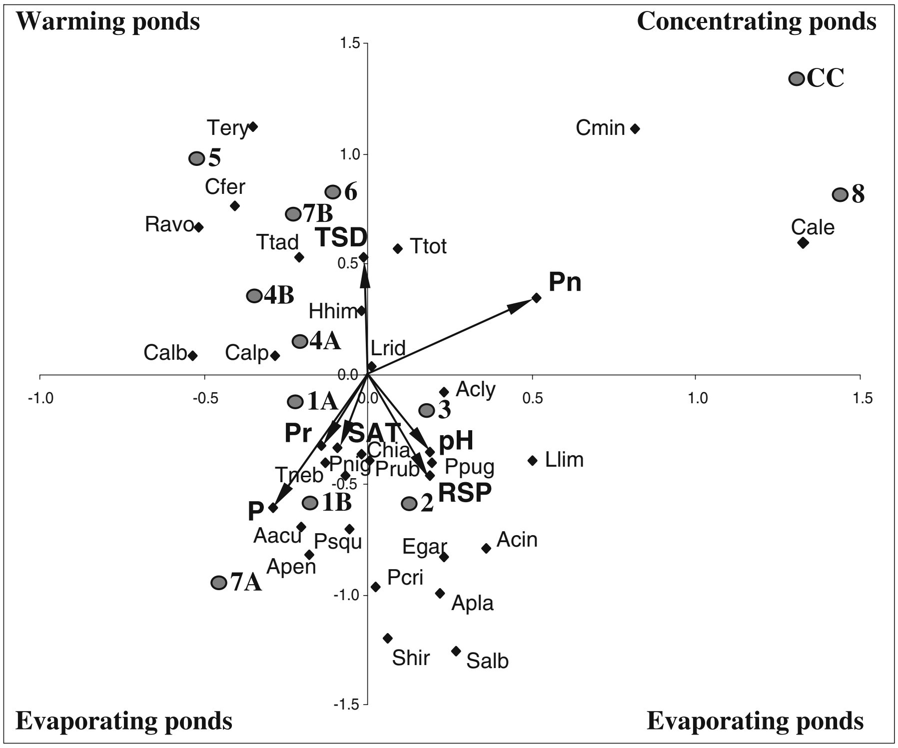

Fig. 3 Distribution of waterbird species and the physicochemical variables on the ordination plane of the CCA. We identified three physicochemical habitats, which coincide with the three groups of ponds characterizing the salt production process: evaporating, warming, and concentrating ponds. The physicochemical variables previously selected by the Monte Carlo test are shown in *bold*: *pH*, depth of the water column (*P*); dissolved oxygen content (*SAT*); lagoon perimeter (*Pr*); total dissolved solids (*TDS*); substrate hardness (*Pn*); and ratio of area to perimeter of the ponds (*RSP*). *Gray dots* indicate the coordinates of the centroids of sampled pond groups in the ordination plane. The abbreviations of the biotic variables are shown in Appendix

Table 3 Relationships between waterbird species and abiotic environment

Variables	Variance explained by the variables (%)	Correlations between variables and canonical axes	
		Axis I	Axis II
P	20.41	−0.29*	−0.60*
Pn	16.69	0.51*	0.34*
pH	12.95	−0.19	−0.35*
Pr	10.15	0.19	−0.46*
RSP	10.15	−0.14	−0.32*
SAT	7.35	−0.09	−0.33*
TSD	6.41	−0.01	0.52*

The variables selected using the Monte Carlo test are shown along with their correlation values with the first two principal axes of the CCA (Axis I 32.7% of variance absorption; Axis II 27.3% of variance absorption)

P water depth, *Pn* hardness of the substrate, *PH* pH, *Pr* perimeter of the lagoon, *RSP* ratio of surface area–perimeter, *SAT* dissolved oxygen, *TSD* total dissolved solids

$^{*}p < 0.005$

dissolved oxygen content is higher, and pH is slightly alkaline.

The plane defined by the first two CCA axes allows three habitats to be characterized in the salinas. The first comprises the group of ponds with a large perimeter, high salinity, hard bed, and shallow water column (Fig. 3). This habitat corresponds to the concentrating ponds. It is occupied by a community poor in bird species, comprising *C. minuta*, *T. totanus*, *C. alexandrinus*, and *L. ridibundus*. A second habitat is hypersaline, with a hard bottom but deeper than the previous one (warming ponds). The birds occupying this habitat are *H. himantopus*, *T. tadorna*, *R. avosetta*, *C. ferruginea*, *C. alpina*, *C. alba*, and *T. erythropus*. The third habitat is less saline and has a soft bottom. These are the deeper evaporating ponds. The water here is slightly alkaline (mean pH 8.2), and the dissolved oxygen content is high. Oxygen content is influenced not only by the lower salinity of the evaporating ponds but also by their higher primary productivity, which is the cause of the slight alkalinity (Margalef 1974).

The perimeter of the evaporating ponds and the surface area/perimeter ratio are the principal differences distinguishing the various evaporating ponds. In 1A, 1B, and 7A, which have a relatively long perimeter for their surface area, the bird community is represented by *A. penelope*, *A. acuta*, *P. squatarola*, *T. nebularia*, and *P. nigricol-*

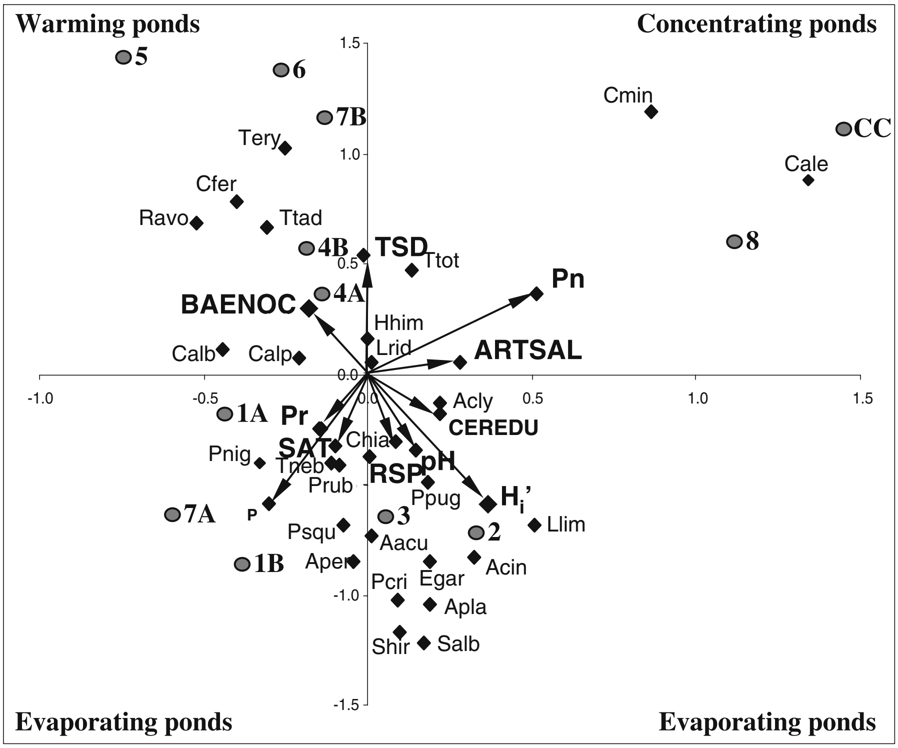

Fig. 4 Distribution of waterbird species and environmental variables, previously selected using the Monte Carlo test, indicating the trophic and physicochemical habitats (selected using the Monte Carlo test) on the ordination plane of the CCA. Three habitats were identified, which coincide with the physicochemical habitats and the three types of ponds characterizing the salt production process: evaporating, warming, and concentrating ponds. *Gray dots* indicate the coordinates of the centroids of sampled pond groups in the ordination plane. The abbreviations of the variables are shown in Appendix

Table 4 Relationships between waterbird species and resource availability

Variables	Variance explained by the variables (%)	Correlations between variables and canonical axes	
		Axis I	Axis II
H'_i	18.71	0.51*	−0.42*
P	17.89	−0.30*	−0.59*
Pn	10.51	0.51*	0.36*
C. edule	8.87	0.08	−0.30*
SAT	7.23	−0.09	−0.32*
PH	5.59	0.18	−0.35*
A. salina	5.59	0.28*	0.05
RSP	4.77	−0.14	−0.28*
Pr	4.77	0.18	−0.48*
TSD	3.95	−0.01	0.54*
B. noctivaga	3.95	−0.27*	0.21

The variables selected using the Monte Carlo test are shown along with their correlation values with the first two principal axes of the CCA (Axis I 28.0% of variance absorption; Axis II 23.9% of variance absorption)

$^{*}p < 0.005$

H'_i diversity of macroinvertebrate species, *P* water depth, *Pn* hardness of substrate, *SAT* dissolved oxygen, *PH* pH, *RSP* ratio of surface area–perimeter, *Pr* perimeter of the lagoon, *TSD* total dissolved solids

lis. In contrast, ponds 2 and 3 have the largest surface area/perimeter ratio. Their bird community consists of *L. limosa*, *A. cinerea*, *A. plathyrhynchos*, *A. clypeata*, *S. albifrons*, *S. hirundo*, *E. garcetta*, *P. cristatus*, *P. pugnax*, *Phoenicopterus rubber*, and *C. hiaticula*.

Relationship between waterbird assemblage and resource availability

The CCA performed on the matrices of bird abundance and trophic resources and physicochemical characteristics (Tables 2 and 3) is summarized in Fig. 4.

The previous Monte Carlo test allowed the most significant variables to be selected (Table 4). With regard to abiotic characteristics, these were the same variables as those obtained from the analysis of matrices [1] and [3]. Likewise, correlation of these variables with the canonical ordination axes was very similar to the previous case, thus, indicating a close association with the physicochemical environments defined (Fig. 3).

Table 5 Diversity values (bits) calculated for the assemblage of waterbirds in the salinas and specifically in the evaporating, warming, and concentration ponds

	Salinas	Evaporating ponds	Warming ponds	Concentrating ponds
Maximum value	3.3	3.3	2.5	2.0
Minimum value	2.0	1.5	0.8	0
Mean value	2.8	2.4	1.6	1.0

C. edule is the most characteristic macroinvertebrate of the most diverse environments with regard to trophic resources and is typical of the evaporating ponds. These ponds support a rich avian community, mainly comprising anatids and other species with a heavy feeding demand, such as herons. The habitat comprises soft substrate, relatively low salinity, and notable depth as revealed by the presence of diving species, good oxygenation, relatively alkaline pH, and large perimeter. These habitat features support a mean waterbird diversity of 2.4 bits (Table 5).

B. noctivaga is the dipteran indicator of deeper water habitats, moderate salinity, and minimal macroinvertebrate diversity. This habitat corresponds to the warming ponds. Lastly, the philopod *A. salina* is the indicator species for the most extreme environments—the shallow concentration ponds—which are poorly oxygenated, highly saline, and contain the hardest substrates. The waterbird community associated with this is the least diverse, consisting mainly of *C. alexandrinus*, *C. minuta*, *Tringa totanus, and L. ridibundus*. The diversity of aquatic birds is reduced to 1.6 bits in the warming ponds and 1 bit in the concentrators (Table 5).

Discussion

There are several reasons for selecting ecological indicators. They can be used to assess the conditions of the environment on the assumption that the presence or absence of, and fluctuations in, these indicators reflect changes taking place at various levels in the ecological hierarchy and also for monitoring trends in ecological conditions over time (Cairns et al. 1993; Noon et al. 1999; Dale and Beyeler 2001). Despite the benefits that indicators can present, they are not widely used as a tool for management and monitoring programs. In this sense, a research priority for conservation biology and applied ecology involves the development and testing of methods for the identification and selection of suitable ecological indicators (Mulder et al. 1999; Vos et al. 2000; Dale and Beyeler 2001; Possingham et al. 2001; Soulé and Orians 2001).

The multivariate analysis developed enabled us to clarify relationships among the physical, chemical, and biological properties of the salinas system and to extract the major similarities and differences in the set of observations and variables considered (Brogueira and Cabeçadas 2006). The stepwise procedure enables us to identify a set of habitats and biotic and abiotic indicators in the coastal salinas studied that can be used to assess the conservation status of these systems from different perspectives and at different observation scales and to design a suitable monitoring program.

The results highlight the existence of two environmental gradients that jointly explain the spatial organization of the biological community studied. One of these is a vertical gradient related to depth, and the other is a horizontal one, determined by the spatial variation in total dissolved solids, as an expression of the variation of the concentration of salts in solution and by the hardness of the pond bed. Moving from the evaporating ponds towards the concentrating ponds, there is a gradual decrease in water depth and degree of oxygenation, and an increase in salinity, pH, and bed hardness.

These gradients discriminate between the more productive saline environments (evaporating ponds) and the hypersaline environments (the warming and concentration lagoons). The latter ones are comparatively poor in trophic resources, although not in their diversity of trophic resources (in the saline and hypersaline habitats identified, there is no significant difference in macroinvertebrate diversity). We observed a differential use of these habitats by the waterbird types. Thus, the anatids form a guild of species that habitually use the evaporating ponds, while the extreme environmental characteristics of the warming and concentration ponds are exploited mainly by limicolous species, whose morphological, trophic, and functional adaptations allow them to successfully exploit this environment (Castro et al. 2000).

The physical and chemical conditions in a given habitat will support a characteristic set of richness and diversity levels of macroinvertebrate species (Heino 2000; Brainwood and Burgin 2006). In the salinas studied, macroinvertebrate diversity differentiates the evaporating ponds from the others and can be considered as a good indicator of these saline environments. Nonetheless, community metrics, such as richness and diversity, can be misleading due to the varying responses of the species to changes associated with variation in the environmental gradient—species more abundant or less abundant with increased stress (Howe et al. 2007). The analyses undertaken differentiated three macroinvertebrate species indicating the main habitats of the salinas: *C. edule*, *B. noctivaga*, and *A. salina* are representative, respectively, of the evaporating, warming, and salt concentrating environments. These three species can be considered as composition indicators, the presence of which identifies representative habitats, and as condition indicators, appropriate for monitoring the effectiveness of conservation and management strategies (Velasquez and Hockey 1991; Zacharias and Roff 2001). The use of biological assemblages as indicators of ecological conditions presents important advantages because the abundance, presence–absence-relative dominance of species and taxa are controlled by environmental processes, provide information on many physical and biological characteristics of a system—i.e., gradients of environmental stress or variation in environmental conditions over time (Urkiaga-Alberdi et al. 1999; Niemi and McDonald 2004; Albani et al. 2007; Howe et al. 2007)—and define the extent of similar environmental conditions. Thus, in our case, for the species less tolerant to salinity, some of which are the staple diet of large birds such as herons, ducks, and flamingoes, the analysis performed highlights *C. edule* as the most representative species in the evaporators, a habitat also used by *E. bicolor*, *B. pavo*, or *A. alba*, all of which are present only in this environment. Likewise, the analysis highlights *B. noctivaga* as the species that indicates high-salinity environments (warming ponds), where large mud-dwelling birds feed, such as the avocet, the black-winged stilt and the black-tailed godwit, among others. Moreover, *A. salina* was shown by the analysis to be the most halo-tolerant species and was mainly found in the concentrators. This species is the basic diet of the smaller mud-dwelling birds.

Conclusion

From a functional point of view, the key factor for the Mediterranean salinas is the gradient of salinity. The salt production process determines ecological partitions within the system. This ecological segregation is very important for conservation of these environments because spatial heterogeneity can provide species with a high diversity of habitat types suitable for migratory waterbirds. Such habitats are nodes of ecological connectivity.

Abiotic and trophic factors associated with the gradient of salinity determine how aquatic birds organize their spatial distribution and activity in the salinas. We characterized macroinvertebrate species as bioindicators. Water depth, substrate hardness, pH, dissolved oxygen, and spatial configuration of the ponds (perimeter and surface area–perimeter ratio) are also of great importance in determining the distribution of the waterbird assemblages and constitute key factors that monitoring programs for salinas tend not to take into account.

An essential component in the design of efficient and cost-effective monitoring programs involves the selection of suitable variables which also enable us to reduce the effort required for successful environmental monitoring. The stepwise procedure developed constitutes a practical tool for this task. Not only does it differentiate the habitats available for the waterbirds but also the biotic and abiotic indicators fundamental to the conservation and management of the salinas as an ecosystem. These variables can then be incorporated into monitoring programs (selection of sampling points and variables) aimed at conserving these systems.

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Appendix

List of biotic variables recorded from the Cabo de Gata salinas and abbreviations used in the tables and figures.

(a) Macroinvertebrate and fish species

PONLIT	*Pontodrilus littoralis*
ABRALB	*Abra alba*
PALELE	*Palaemon elegans*
IDOBAS	*Idotea basteri*
OCTBIF	*Octhebius bifoveolatus*
OCTPUN	*Octhebius punctatus*
CULSP	*Culex* spp.
BAENOC	*Baeotendipes noctivaga*
HYDACU	*Hydrobia acuta*
CEREDU	*Cerastoderma edule*
ARTSAL	*Artemia salina*
ENOBIC	*Enochrus bicolor*
NEBCER	*Nebrioporus ceresvi*
HYDSP	*Hydrophorus* spp.
EPHSP	*Ephydra* spp.
BLEPAV	*Blenius pavo*

(b) Waterbird species

Pcri	*Podiceps cristatus*
Acin	*Ardea cinerea*
Prub	*Phoenicopterus ruber roseus*
Apla	*Anas plathyrhynchos*
Acly	*Anas clypeata*
Hhim	*Himantopus himantopus*
Cale	*Charadrius alexandrinus*
Psqu	*Pluvialis squatarola*
Calp	*Calidris alpina*
Calb	*Calidris alba*
Tneb	*Tringa nebularia*
Ppug	*Philomachus pugnax*
Lrid	*Larus ridibundus*
Shir	*Sterna hirundo*
Pnig	*Podiceps nigricollis*
Egar	*Egretta garcetta*

Ttad	*Tadorna tadorna*
Apen	*Anas penelope*
Aacu	*Anas acuta*
Ravo	*Recurvirostra avosetta*
Chia	*Charadrius hiaticula*
Cfer	*Calidris ferruginea*
Cmin	*Calidris minuta*
Ttot	*Tringa totanus*
Tery	*Tringa erythropus*
Llim	*Limosa limosa*
Salb	*Sterna albifrons*

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