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Spatiotemporal Assessment of Littoral Waterbirds for Establishing Ecological Indicators of Mediterranean Coastal Lagoons

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Abstract: Waterbirds are vital indicators of anthropogenic influence on the ecological status of Mediterranean coastal lagoons. Our study relates temporal waterbird data to key environmental gradients at catchment scale that have a structural or functional influence on littoral waterbird assemblages at different scales. During two full-year cycles and two additional wintering seasons, the nearshore waterbird assemblages of the Mar Menor coastal lagoon (Murcia Region, SE Spain) were monitored monthly. Several biological indicator variables were related to the anthropogenic environmental gradient in the catchment area. Results showed that there was a strong dependence of waterbird assemblages on the distance to shore, emphasizing the importance of the first 100-m band, in which many species relevant to conservation converge on food resources. Well-preserved shoreline tracts therefore had a clear positive effect on community richness and diversity values, and were correlated with the occurrence of some species. These results clearly support the need for effective protection and restoration measures of such littoral habitats. Specific responses to local disturbing processes were nested within habitat and landscape preferences, supporting the value of aquatic birds as integrative ecological signals in semi-enclosed coastal systems. Moreover, waterbird-based indicators responded positively to environmental improvements both qualitatively and quantitatively.

Keywords: waterbirds assemblages; ecological indicators; coastal lagoon; anthropogenic landscape gradient; natural habitats; land-use/land-cover; spatiotemporal assessment

1. Introduction

The need to understand how wildlife responds to the broad-ranging impacts of development is becoming increasingly important as human populations continue to grow and urbanization spreads around the globe [1]. Integrated, quantitative expressions of anthropogenic stress over large geographic areas (e.g., watersheds and their associated aquatic ecosystems) can be valuable tools in environmental research and management, and a basis for the study of the response of key indicator taxa to anthropogenic pressure [2,3]. The identification of potential indicator species, their monitoring, and the ecological quantification of their responses have been proven to be useful tools in environmental management [4]. In this regard, relating ecological status to anthropogenic landscape processes helps in the development of cost-effective environmental indicators and in the implementation of remedial action [5]. The Water Framework Directive [6] requires the monitoring and management of the ecological status of surface waters by all Member States, including coastal and transitional ones [7].

Coastal lagoons (CLs), as semi-enclosed coastal systems, and Mediterranean lagoons in particular, are especially threatened by human stressors given the high occurrence of intensive activities associated with a dense human population around them [8,9].

The role of waterbirds as environmental indicators has been widely recognized and addressed both in general reviews [10,11] and specific case studies [12–15]. Many studies on the effects of human activities on waterbirds have been conducted in well-preserved habitats, often within nature reserves or areas managed for conservation [16]. However, wetland ecosystems close to high-density urban areas, which also provide valuable habitats for waterbirds, may experience greater pressure from human activities through modifications of their surrounding landscape characteristics [17]. In this regard, watershed processes can result in severe structural or functional changes for waterbird populations, even without direct habitat alteration [18–21]. The scale at which abiotic structural or functional perturbations occur will determine different scenarios: immediate habitat-scale processes are probably associated with a positive or negative structural effect (vegetation cover, disturbing physical elements, etc.). On the other hand, responses to landscape configuration in upland areas or in the whole catchment can also have a structural basis in some cases [22,23], but very often a functional one, through the influence of processes like intensification of agricultural irrigation and fertilization or urban pollution [24–26]. Thus only the combined analysis of biological responses on both local and landscape scales will be useful for the integrated management of wetland communities and their associated terrestrial landscapes in a context of environmental anthropogenic change [27].

Waterbirds stand out as one of the main criteria for the designation of internationally important wetlands, especially under the Ramsar Convention [28]. However, except for some monitoring activities, birds have received little scientific attention in coastal lagoons compared to the research efforts directed to other taxa, such as macroinvertebrates or fishes, ignoring their vital role in the ecosystem as top predators and their contribution to underlying ecological processes [29]. Moreover, regular waterbird monitoring data are rarely used in the development of environmental policy and management activities, with the exception of Ramsar wetlands designation and the Natura 2000 Network evaluation [30]. Furthermore, birds are not even included in the WFD's assessment of European waters. However, knowledge of their response to anthropogenic pressures could serve to harmonize the WFD's water ecological quality targets with the biodiversity conservation objectives set by other EU Directives (such as the Birds and Habitats Directives and the EU Biodiversity Strategy to 2020; [31]). Such information can be especially useful in complex areas like Mediterranean coastal lagoons and their associated wetlands, where many nature conservation regulations and human activities overlap.

Waterbird communities are among the most important biological components of the Mar Menor coastal lagoon, which is subjected to a variety of environmental pressures [32–37]. In fact, the lagoon has been designated as a Special Protection Area for its birds populations contained in the species annex I of the Birds Directive 2009/147/CEE. A wide variety of flag species coexist, such as the Little egret (*Egretta garzetta*), the Black-winged (*Himantopus himantopus*) and the Lesser Short-toed Lark (*Calandrella rufescens*) occur in this area, as well as species that are indicative of agricultural intensification and urban development, such as grebes (*Podiceps nigricollis* and *Podiceps cristatus*) and Red-breasted Merganser (*Mergus serrator*) [24,38]. The lagoon represents a key natural resource for a large area of influence, the Campo de Cartagena coastal plain, to which it provides a variety of natural resources and services, like fisheries, salt, recreation, and tourism, while at the same time being affected by several pressures from upland areas (e.g., hydrological alterations, chemical inputs, and structural modifications). Consequently, the lagoon has been studied in several ecological and environmental aspects [39–43], some of them focusing on waterbirds and their relationship with long-term environmental change and local spatiotemporal gradients [44,45]. However, a critical part of the lagoon waterbird community lacks specific studies, i.e., the most dynamic, productive and directly pressured sections near the shore. The dynamism and transitional character of this area enable a high diversity of ecological niches, thus bringing together a high functional diversity of waterbird species

(divers, swimmers, waders, etc.). Previous studies related to transitional and shallow coastal areas have focused on the relationship between waterbird indices and environmental gradients at different geographical scales [3,16,46]. Thus, this study aimed at filling this gap in the Mar Menor lagoon, looking for relationships between indices of waterbird use of the littoral sections and descriptors of human pressure in their areas of influence.

The specific objectives of this study were (1) to evaluate the spatial and temporal variation of waterbird-based indices in the nearshore habitats of the lagoon; (2) to identify indicator species of different types of nearshore habitats (in relation to land use and stress gradients at different spatial scales); (3) to describe the relationship between the environmental gradients and quantitative measures of waterbird indicator species and biological indices; and (4) to propose management strategies for the nearshore lagoon sections and their surrounding terrestrial landscape, which maximize ornithological value while preserving the ecological integrity of the lagoon ecosystem, in order to support the objectives of the European Union's Water, Birds and Habitats Directives, as well as the EU Biodiversity Strategy to 2020.

2. Materials and Methods

2.1. Study Area

The Mar Menor is a hypersaline coastal lagoon located in southeastern Spain (Figure 1). With a surface of 135 km^2 and an average depth of 4 m [47], it is the largest coastal lagoon of the western Mediterranean. It is surrounded by ca. 600 km^2 of irrigated agricultural plain inside a total watershed area of 1275 km^2 [48] with dense touristic urban developments, and it is almost enclosed from the Mediterranean Sea by a sand bar, also dominated by urban development. Since 1994, the Mar Menor is also designated as a Ramsar Site and since 2001 as a Bird SPA and a Specially Protected Area of Mediterranean Importance. The coastline is fringed by patches of saltmarsh and salt steppes and a former salt works that was abandoned during the 20th century, interspersed with agricultural (traditional or intensive) and urban areas.

The Tajo-Segura river diversion started draining the Campo de Cartagena coastal plain in the 1980s, changing its agricultural use from extensive dryland and traditional groundwater-fed to intensively irrigated crops. This caused significant hydrological changes (e.g., phreatic level rise and permanent agricultural drainages), and subsequently affected the structure and relative distribution of natural littoral habitats [18]. Other major physical and hydrological changes started earlier in the 1970s due to the dredging of one of the channels linking the lagoon with the sea, which increased the marine influences, starting a process of "mediterraneization" [30] that resulted in a more marked continental–oceanic gradient within the lagoon [49].
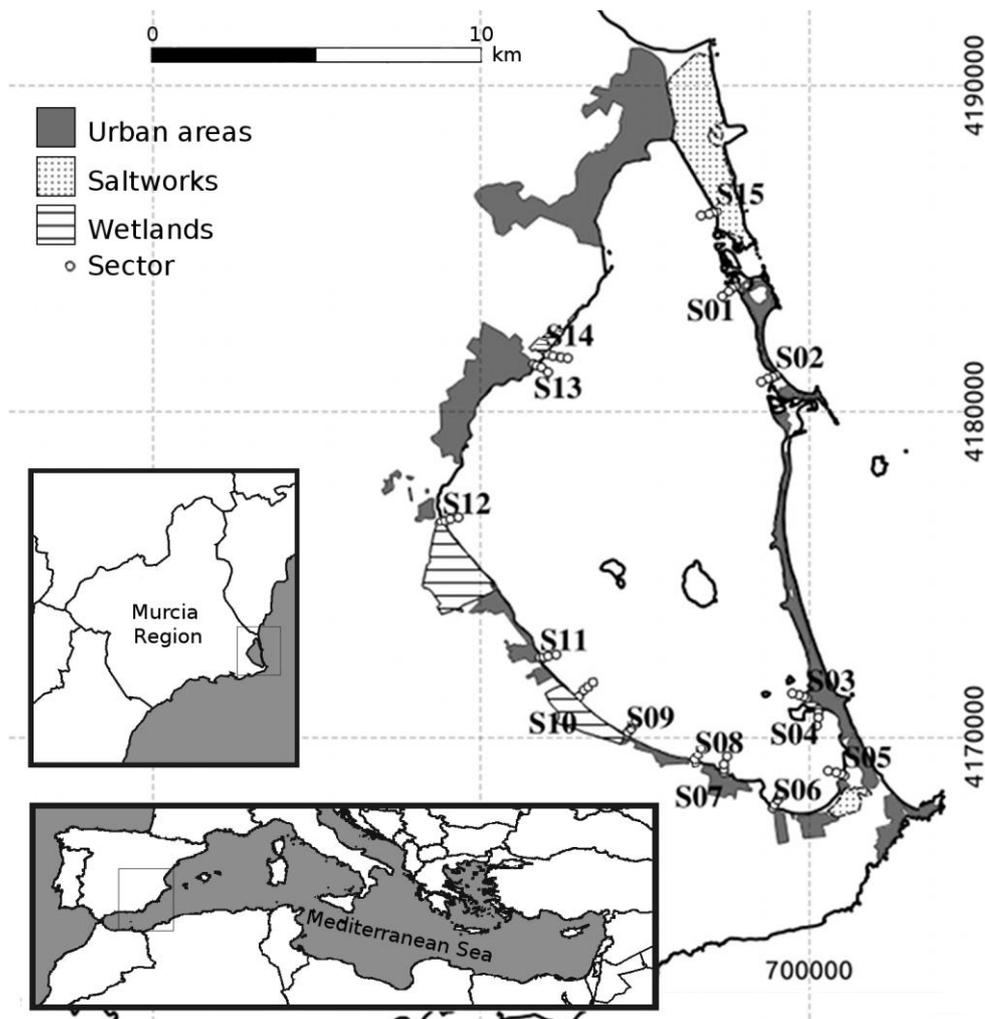
Figure 1. General map of the Mar Menor Lagoon showing the 15 bird sampling stations within three sectors: the urban areas, the active saltpans, and the wetlands (natural saline steppe areas and other phreatophytic formations). The map projection corresponds to ED50 UTM 30N.

2.2. Bird Census

Monthly counts of waterbirds were conducted from October 2006 to October 2008 (two full annual cycles) and from October 2009 to March 2010 and October 2010 to March 2011 (two distinct wintering seasons) at 15 sampling stations distributed along the lagoon shoreline (Figure 1; see also [45]). Sampling stations were representative of the main diversity of structural and functional characteristics of shoreline habitats in the lagoon. All waterbird species were counted except for small shorebirds. The criterion was to include species able to exploit the widest range of the studied sections. Therefore, small wading birds (e.g., *Calidris* spp., *Charadrius* spp., etc.) were excluded as they are mainly restricted to micro-tidal habitats due to their morphology and their abundance in the lagoon is much lower than in nearby wetlands.

Following [14], the nearshore water section adjacent to each observation point was divided into four parallel bands at different distances from the shore (B1 = 0−100 m, B2 = 100−250 m, B3 = 250−500 m, B4 = 500−1000 m), resulting in 60 sampling units (four bands × 15 sampling stations). The outer limit of the B4 band was set at 1000 m since birds could not be adequately identified beyond this limit. Each sampling station included 500 m of shoreline. The same observer, trained in the estimate of distances, did all the censuses in order to minimize observer bias. The total abundance of

each species was recorded in each unit during a 10 min observation period (per station) performed within the first 6 h of daylight. The starting station of the waterbird census alternated between S01 and S05 every month in order to minimize the effect of the time of the day on bird distribution.

2.3. Data Analyses

2.3.1. Bird Data

Based on previous studies from this area [44] and general recommendations from the waterbird monitoring literature [50], monthly bird counts were grouped into two seasons: summer (April to September) and winter (October to March). Although there is some overlap in the spring and autumn transition months, from an ecological perspective community organization is well suited to that temporal division since there are two well-defined phenology-based waterbird communities [38].

Three biotic indices were calculated for each sampling unit (station × band): Richness (R), Shannon–Wiener Diversity (H) and Total Bird Use (TBU). Non-parametric analyses of variance based on the Wilcoxon Test were used to analyze inter-seasonal (winter vs. summer) and inter-annual (between summers) differences (for factor classes ≤2), whereas the Kruskall–Wallis Test was used to analyze differences between winter seasons (inter-annual), sampling stations (lagoon's spatial heterogeneity), and bands (site heterogeneity) (for factor classes >2). Statistical significance was set at $p = 0.05$. When overall significant differences occurred, post hoc paired comparisons were performed with the "pgirmess" package (http://giraudoux.pagesperso-orange.fr/). Finally, to assess the variation of indices in relation to the distance to shore linear regressions were performed with distance bands from the shore (BAND) as the independent variable. Most statistical analyses were conducted with the freely distributed R software [51]. After data transformation (log [x + 1]), a Non-metric Multi-Dimensional Scaling (NMDS) ordination [52] was performed with Primer v6 software [53] to analyze the effect of distance from the shore on the waterbird community composition.

2.3.2. Definition of Landscape Gradients and Selection of Environmental Predictors

To detect the main stress factors and land use/cover gradients affecting the lagoon two sets of environmental variables were first evaluated (Table 1), based on spatial analysis using GRASS GIS 6 [54]. The first set of environmental variables studied corresponded to measures of distance to important shelter/disturbing elements selected on the basis of previous studies [44]. The second set of environmental variables comprised the surface of the land cover types inside buffer areas surrounding each sampling station at two spatial scales [16]: 100 m buffer and 1000−100 m buffer (1000 m ring hereafter). Land cover types were obtained by means of remoted sensing [4,55,56] and are available online [57]. All environmental variables were summarized using Principal Component Analysis (PCA) in order to detect redundancy between variables [58] and to select the variables that best described anthropogenic stress, landscape structure and functionality, according to [3].

After the selection and interpretation of nine PCs (see Table S1 and Figure S1 in supplementary online material), those environmental variables with a high correlation with an axis (Pearson's coefficient >0.6) were finally selected as representative descriptors of such gradient. Likewise, sampling stations were classified on the basis of their scores on such PCs through a NMDS classification analysis (using Euclidean distance). This resulted in four well defined groups (see Figure S2 in supplementary online material), which were used as a grouping factor in an Indicator Value Analysis (IndVal) based on a Monte Carlo test, in order to identify the most representative species of each group (on the basis of their relative abundance). This was performed with PC-Ord software [59], separately for the winter and summer waterbird assemblages. Statistically significant indicator species (at $p < 0.05$) were selected as the candidate dependent variables to be included in multiple regression models (see Section 2.3.3).

Table 1. Description of the environmental variables used to identify the main pressure factors and land use/cover gradients affecting the lagoon.

VARIABLE ACRONYM	DESCRIPTION
Spatial and Temporal Factors	
STATION	Sampling stations (S1 to S15)
BAND	Different distance to shore (B1 = 100 m, B2 = 100−250 m, B3 = 250−500 m, B4 = 500−1000 m)
YEAR	Consecutive years of sampling (year 1 = annual cycle from October 2006 to October 2007; year 2 = annual cycle from October 2007 to October 2008; year 3 and year 4 correspond to the wintering periods of 2009/2010 and 2010/2011 respectively)
Distance to Disturbing or Shelter Elements	
DMMI	Distance to nearest lagoon island
DMEI	Distance to nearest Mediterranean island
DCAN	Distance to communication channel (Estacio Channel) with the Mediterranean Sea
DALB	Distance to main permanent discharge focus (Albujón ephemeral river mouth)
DURB	Distance to nearest urban centre
DHARB	Distance to nearest harbour
DAIR	Distance to airport (San Javier Airport)
DCSAL	Distance to nearest saltpan (industrial area with shelter role for waterbirds)
DCWET	Distance to nearest natural wetland (protected area with shelter role for waterbirds)
Land Cover (Measured at 100 m, 1000 m, and Sub-Basin Scale)	
NDW	Natural dense wooded (*Acacia sp.*, *Pinus sp.*)
NCW	Natural clear wooded (*Acacia sp.*, *Pinus sp.*)
NDS	Natural dense scrub (saline steppe and saltmarsh scrub)
NCS	Natural clear scrub (saline steppe and saltmarsh scrub)
DCW	Dry arboreal crops
DCS	Dry herbaceous crops
ICW	Irrigated arboreal crops (orchards)
ICS	Irrigated herbaceous and horticultural crops
UNP	Unproductive (urban areas)
WBS	Water bodies (different pond types)

2.3.3. Multiple Regression Models

In order to analyze the relationship between waterbird indices and environmental factors, several multiple regression models were performed. Using ecological indices as dependent variables (TBU, R and H), the following procedure was followed: first, the stations where indices' mean scores reached extreme values were identified; second, the axes with which these stations were most associated were selected based on their scores in the PCA; third, the variables with a higher Pearson's correlation coefficient with these axes (Pearson's correlation coefficient >0.6) were finally selected as input variables in GLMMs. Using indicator species' bird use, the groups of sampling stations (from Cluster classification of PCs and IndVal analysis) were the basis for selection: input variables were selected when they showed a Pearson's correlation coefficient >0.6 with the axis (PC) to which sampling stations that shaped the group were associated. In relation to community indices, the ultimate criteria to perform a model were the results of the previous analyses of variance in relation to spatial factors: if significant differences were detected for an index, the regression analysis sought to identify the landscape or habitat factors most contributing to these differences. Different distributions of the dependent variables were found: normal distribution in the case of the Shannon Index and Poisson distribution for Total Bird Use, Richness and Bird Use of selected indicator species), which were analyzed using linear mixed models and generalized linear mixed models, respectively.

The procedure of model selection was based on lowering the Akaike information criterion (AIC; [60]) and including explanatory variables that showed statistically significant effects ($p < 0.05$). Three factors with spatial or temporal effects were included in the regression models, two as fixed grouping factors: BAND (to integrate the effect of distance to shore) and YEAR (to integrate the effect

of time); and a third one as a random grouping factor: STATION (to integrate the variability of inherent conditions of each sampling station not studied specifically in this paper).

3. Results

3.1. Spatiotemporal Variation of Waterbird-Based Indices

Waterbird census results are shown in Table S2 in supplementary online material. The statistical significance of temporal and spatial variation in waterbird indices is shown in Table 2. Significant differences between winter and summer in TBU, R and H were consistent with the separate treatment of their respective waterbird communities.

TBU, R and H showed significant differences for temporal (YEAR) and spatial factors (sampling station, BAND). In addition, linear regressions showed a decrease of three indices with BAND (lower values at higher distances from the shore): TBU (Adj. R^2 = 0.05, $p < 2.57 \times 10^{-5}$), R (Adj. R^2 = 0.25, $p < 2.26 \times 10^{-16}$) and H (Adj. R^2 = 0.148, $p < 1.17 \times 10^{-12}$.). In summer, TBU showed significant differences between sampling stations as well as between bands; R showed significant differences between years and also between bands, whereas H only showed significant differences between bands. Linear regressions also showed a decrease of TBU (Adj. R^2 = 0.199, $p < 2.33 \times 10^{-6}$), R (Adj. R^2 = 0.507, $p < 2.2 \times 10^{-16}$), and H (Adj. R^2 = 0.55, $p < 2.2 \times 10^{-16}$) with BAND. Noteworthy are the results of post-hoc tests of differences in community structural indices (R and H) in relation to BAND, showing a significant change between B1 and the remaining bands (2–4). Also remarkably, in winter TBU did not differ significantly between B1 and B4, but with respect to B2 and B3, while in summer it behaved like other indices (B1 differs from the remaining bands). Finally, in both seasons, the NMDS ordination confirmed that community composition changed markedly from B1 to B2–B4 (NMDS stress = 0.17 in both seasons). Thus, BAND represented a key factor for community organization, which supported considering it as a fixed grouping factor in all subsequent multiple regression analyses. On the other hand, TBU should be also integrated into regression analysis as a random grouping factor to consider the effects due to inter-annual population fluctuations.

Table 2. *p*-Values of Kruskall–Wallis and Wilcoxon tests performed on waterbird community indexes in relation to temporal and spatial class variables. The Wilcoxon test was conducted for factors with only two classes: "season" (summer/winter) and "year" (only for the summer waterbird community, sampled twice). Kruskall–Wallis test was conducted for factors with more than classes: "station" and "band" in both seasons, and "year" (for the wintering waterbird community, sampled four times). n.s. = Non-significant.

	Annual	Winter				Summer			
Variables	**Season**	**Year**	**Sampling Station**	**Band**	**Post Hoc "Band"**	**Year**	**Sampling Station**	**Band**	**Post Hoc "Band"**
Total Bird Use	$<2.26 \times 10^{-16}$	6.30×10^{-3}	0.00078	4.30×10^{-3}	B1, B4 vs. B2, B3	n.s.	0.04	1.88×10^{-7}	B1 vs. B2 to B4
Richness	$<2.26 \times 10^{-16}$	2.55×10^{-2}	0.0013	6.94×10^{-8}	B1 vs. B2 to B4	0.0411	n.s.	6.39×10^{-12}	B1 vs. B2 to B4
Shannon–Wiener Diversity	$<2.26 \times 10^{-16}$	2.76×10^{-2}	0.012	0.00087	B1 vs. B2 to B4	n.s.	n.s.	1.0×10^{-13}	B1 vs. B2 to B4

3.2. Indicator Species, Community Indices, and Influential Gradients

Results of the IndVal analyses for the four well-defined groups of sampling stations are shown in Table 3. Seven indicator species with statistical significance were identified, three in winter (*Larus genei*, *Sterna sandvicensis*, and *Podiceps cristatus*) and four in summer (*Fulica atra*, *P. cristatus*, *Sterna albifrons*, *Larus michahellis*, and *Egretta garzetta*), which were used as dependent variables in multiple regression models. Table 3 also shows the gradients a priori considered most influential for each group of stations on the basis of individual waterbird species' use. In the same way, Table 4 shows the sampling stations where community indices reached extreme mean values, and the gradients (PCs) to which those stations were associated (from PCAs scores).

Table 3. Sampling stations grouped by Cluster classification (structural-functional groups) from the first three axes of all the PCAs performed. Also shown are the Indicator Species for each group (from IndVal analyses), the season when the indicator value is statistically significant and the influential environmental gradients (PCs) for each species (clear association of preferred stations with axes).

Group	Stations	Description	Indicator Species	IV Significance	Season	Influential Gradient
1	S15	Natural area exposed to oceanic (=Mediterranean) influence. Patches of *Pinus halepensis* and water bodies (saltpans); absence of structural disturbing elements of anthropogenic origin	*Larus genei*	0.021	Winter	PC2-b100, PC3-b100, PC1_r1000, PC2_r1000, PC2-dist, PC3-dist
2	S1, S2	Semi-natural area exposed to oceanic influence. Incipient urbanization; close to disturbing structural anthropogenic elements	*Sterna sandvicensis*	0.035	Winter	PC1-r1000, PC2-dist
3	S13, S14	Transitional area (urban-agricultural) of internal shore, influenced by land-based disturbing functional elements (point and diffuse effluent discharges); close to important disturbing structural anthropogenic elements (e.g., airport)	*Fulica atra*	0.036	Summer	PC1-r1000, PC1-dist
4	S10, S12	Inland shore with natural scrub (saline steppe, saltmarsh), influenced by land-based disturbing functional elements (point and diffuse effluent discharges); absence of disturbing structural anthropogenic elements.	*Podiceps cristatus* *Sterna albifrons* *Larus michaellis* *Eggretta garzetta*	0.003 0.005 0.034 0.008	Winter Summer Summer Summer	PC1-b100, PC3-b100, PC2-r1000, PC1-dist

Table 4. Waterbird community indices and the influential gradient affecting them as defined by the maximum and minimum values reached by these indices in sampling stations and by the clear association of these extreme stations with environmental gradients (from PCA interpretation).

Index	Season	Sampling Stations	Value	Influential Gradient
Bird Use	Winter	S12, S2 S4	Max Min	$PC1_{b100}$, $PC2_{r1000}$ $PC1_{dist}$, $PC2_{b100}$
	Summer	S12, S10 S4	Max Min	$PC1_{b100}$, $PC2_{r1000}$ $PC1_{dist}$, $PC2_{b100}$
Richness	Winter	S12, S1 S3, S4	Max Min	$PC2_{b100}$ $PC1_{r1000}$, $PC3_{r1000}$, $PC1_{dist}$
Shannon Diversity	Winter	S11, S13 S9, S3	Max Min	$PC1_{dist}$ $PC1_{b100}$

3.3. Multiple Regression Models

The results of GLMMs are shown in Table 5, which includes, for each model, the variables involved (in order of importance) and the total deviance explained (%). Following our final selection

criteria, multiple regression models for R and H in summer were not considered since there were no significant differences for any of these indices between sampling stations. Additionally, Table S3 in supplementary online material shows the value of the β coefficient and the sign affecting each dependent variable (each factor class in the case of categorical variables).

Table 5. Multiple regression models of indices and indicator species.

MODEL	Explained Deviance	Factor Classes Observations
Winter		
Total Bird Use~Band + Year	20.41%	$(-)$B2 $(-)$B3 $(-)$B4 $(-)$Year2 $(-)$Year3 $(-)$Year4
Richness~Band + Year + $\text{Nds}_{b100} - \text{Nds}_{b100}^2 - \text{Icw}_{b100}$	39.92%	$(-)$B2 $(-)$B3 $(-)$B4 $(+)$Year2 $(+)$Year3 $(+)$Year4
Shannon Diversity~Band + Year	9.16%	$(-)$B2 $(-)$B3 $(-)$B4 $(+)$Year2 $(+)$Year3 $(+)$Year4
Use of *Podiceps cristatus*~Band + Year + $\text{Nds}_{r1000} - \text{Dmmi} + \text{Dmmi}^2$	57.42%	$(+)$B2 $(+)$B3 $(+)$B4 $(-)$Year2 $(+)$Year3 $(+)$Year4
Use of *Larus genei*~Band + Year + $\text{Ndw}_{r1000} + \text{Ncs}_{b100} - \text{Ncs}_{b100}^2$	81.8%	$(-)$B2 $(-)$B3 $(-)$B4 $(-)$Year2 $(-)$Year3 $(+)$Year4
Use of *Sterna sandvicensis*~Band + Year $-$ Dcan	44.39%	$(-)$B2 $(-)$B3 $(-)$B4 $(+)$Year2 $(+)$Year3 $(-)$Year4
Summer		
Total Bird Use~Band + Year + Dcsal + $\text{Wbs}_{r1000} - \text{Wbs}_{r1000}^2$	51.25%	$(-)$B2 $(-)$B3 $(-)$B4 $(+)$Year2
Use of *Fulica atra*~Band $-$ Year + $\text{Nds}_{r1000} - \text{Ics}_{r1000} + \text{Ics}_{r1000}^2$	44.16%	$(-)$B2 $(-)$B3 $(-)$B4 $(+)$Year2
Use of *Sterna albifrons*~Band + Year $-$ Dcwet + Dmmi + Ncs_{b100}	89.53%	$(-)$B2 $(-)$B3 $(-)$B4 $(-)$Year2
Use of *Larus michaellis*~Band + Year + Ncs_{b100}	36.98%	$(-)$B2 $(-)$B3 $(-)$B4 $(+)$Year2
Use of *Eggretta garzetta*~Band + Year + $\text{Nds}_{b100} + \text{Ncs}_{r1000}$	57.76%	$(-)$B2 $(-)$B3 $(-)$B4 $(-)$Year2

4. Discussion

Our study showed that in such semi-enclosed coastal lagoon systems, the richness and abundance of waterbirds can be favored under moderate degradation states (i.e., eutrophication), but usually only in the presence of well-preserved natural environments (NDS, NCS) that act as buffers for pollution in the long term. The influence of such natural features and of internal lagoon gradients diminishes the secondary effects of anthropogenic landscape impacts. High waterbird richness and the presence of key indicator species of special conservation concern (i.e., *L. genei*, *S. sandvicensis*; [61]) indicate the structural and functional features of the best preserved lagoon habitats, including healthy adjacent landscapes providing refuge or buffering land-based impacts. Therefore, the control of eutrophication will favor specialist waterbird species [62], usually of great conservation value, while reducing the abundance of generalist ones. The consideration of both types of responses (general to natural areas, and local to disturbing processes) enhances the value of waterbirds as integrative environmental indicators compared to other bioindicators (e.g., benthic biocoenoses, fish assemblages), which nevertheless can complement the assessment of local ecological condition.

4.1. Spatial and Temporal Variation of Waterbird-Based Indices

Significant differences between years, sampling stations and bands appeared in all cases for winter indices. YEAR expressed temporal changes in waterbird populations reflected in local surveys, but partly due to processes operating at larger scales (e.g., reproductive success, migration patterns,

survival; [63]), and partly due to local interannual changes [64,65]. Since BAND was a measure of the distance to attractive or deterrent shoreline features, the decrease of H and R from B1 to B2–B4 suggested that winter community structure was affected by them, as well as by depth (inversely related with BAND), which determines the distribution of bird morphological types, feeding styles and foraging strategies [66,67]. In addition, several species exploiting the first band (herons, terns, coot, etc.) were attracted by specific food patches located in shallow areas, i.e., macrophyte meadows, algal mats, and their associated invertebrate and fish communities [68,69]. In the summer period, significant differences were found only between bands for all indices, and in one case between stations (TBU) or years (R). The general decline in the value of indexes with respect to winter and the remarkable absence of differences in R and H between stations were indicative of community impoverishment and homogenization. Variation of TBU was probably due to increased stress from seasonal tourism in urban-affected areas [44], which force summer species to concentrate in less anthropogenic ones. The overwhelming influence of BAND and YEAR does not imply that the responses to other variables should be disregarded, but that their effects must be isolated from local environmental factors [70].

4.2. Community Indices' Models

The negative response to BAND of both winter and summer TBU and R was consistent with the eco-morphological requirements of species. Band 1 offers a greater variety of foraging niches and food resources on which different strategies and morphotypes can coexist, but this effect is reduced with distance as depth increases. Higher β in the response of summer TBU indicated a lower abundance of waterbirds in deeper waters with respect to winter, probably related to the increase of water-based recreational activities [44]. Maximum winter values of TBU and R were recorded in stations of transitional environments with very pronounced gradients: continental-lagoon in the main ephemeral river mouth (S12), and lagoon-marine in areas adjacent to sea openings (S2 and S1). Although they are structurally and functionally very different, all three areas probably offer a high diversity of trophic resources, rich food patches, and more feeding niches. Furthermore, areas where TBU peaks in summer (S12, S10) were far from saltpans and their disturbed vicinity, hence waterbirds would prefer these natural shorelines with less human presence (positive response of summer TBU to DCSAL). Moreover, they are close to alternative inland feeding habitats (natural and restored ponds, old sewage works, irrigation ponds; Reference [71], which was reflected in a positive quadratic response of summer TBU to the presence of waterbodies in the first 1000 m inland (WBS_ r1000).

There was a positive quadratic response of winter R to well preserved salt steppe or saltmarsh (NDS) in the first 100 m of land, which is the original, structurally undisturbed landscape of the lagoon inland shoreline [18]. This is consistent with the results of [13], where less human-impacted and structurally more heterogeneous stations showed higher bird richness and diversity. By contrast, the negative response to irrigated arboreal crops in the 100 m buffer (ICW_b100) suggested a negative functional influence (subsurface diffusion of agricultural drainage causing eutrophication), or a negative perception of vegetation structure (disruption of the traditional open landscape). Both effects are compatible with a reduction of bird richness through the displacement of the less tolerant species.

A gradient of increasing diversity related with proximity to the Mediterranean sea, recognized in the Mar Menor lagoon for several other aquatic taxa [72] has previously been proposed by [44] and was also identified in the present study (high richness in S2 and max in S1), and also considering the influence of terrestrial habitats (richness and/or diversity are also favored by natural landscapes, e.g., NDS) (Tables 4 and 5). In fact, the most diverse areas for waterbirds share the characteristics of being more natural and closer to the open sea. Only S2 is a low-quality habitat based both on benthic indicators [42] and on terrestrial features (urban), but its openness to the main sea could offset these limitations, leading to high waterbird diversity. Therefore, the disconnection from the Mediterranean Sea would explain the minimum waterbird value of other sections with similar impacts (S3 and S4).

4.3. Wintering Indicator Species' Models

On the basis of different ecomorphological requirements, waterbirds responded specifically to distance to shore: positively in the case of *P. cristatus* (diver) and negatively for *S. sandivcensis* and *L. genei* (shallow water feeders). *P. cristatus* also responded positively to NDS in the first 1000 m. In fact, [69] reported high densities and biomasses of littoral (in S12) and benthic fishes (in S10 to S12), which could benefit piscivorous species like *P. cristatus*. However, its preference for natural stations (S10, S12) subject to the diffusion of agricultural drainage, could manifest a background response to the functional influence of landscape processes (i.e., agricultural pollution) previously suggested by [15]. On the other hand, *L. genei* responded positively to NCS in the first 100 m and to NDW in the subsequent 900 m (1000 m ring). In practice these areas represent sparse saline steppe and saltmarsh habitats with a second vegetation belt composed of tall helophytes—favored by agricultural irrigation, invasive *Acacia* sp. or *Pinus halepensis* woodlots (like in S15, where *L. genei* is indicator species). Despite the implications of invasive trees for conservation, this habitat combination should be regarded as the species' landscape template. Finally, *S. sandvicensis* was tied to areas closest to the functional lagoon mouth: S1 (natural section adjacent to S15, a protected area), and S2 (more disturbed urban section). It seemed therefore more influenced by the trophic advantage represented by the proximity and communication with open waters [44], belonging to an adjacent Important Bird Area and reported as a valuable feeding area for seabirds [73].

4.4. Summer Indicator Species' Models

The negative response of all indicator species to distance to shore was due to their preference for shallow feeding areas rich in food resources for both phytophagous and fish-eating species. The indicator character of *F. atra* in summer in S13 and S14 seemed to be inconsistent with its phenology and habitat preferences, but could be explained by the concentration of part of the population in traditional palustrine habitats of the inner shore during transition months (April, October). *F. atra* also presented a positive quadratic response to irrigated herbaceous crops in the first 900 m ring of land, for which it has been attributed and indicator role of eutrophication [14,15]. *S. albifrons* showed a strong negative response to the distance to shore (reflected by most of the model's deviance explained by BAND), regardless of shore habitat naturalness. For other tern species [44,74] pointed to a low specific sensitivity to human disturbance and to aerial foraging [75], as possible explanations for their distribution. The marginal effect of other variables highlights the negative response to distance to the nearest wetland and the positive response to NCS in the first 100 m. As indicator species of S10 and S12 (natural stations near wetlands like marshes with ponds), its reluctance to move away from the shoreline can also reflect some preference for such habitats.

L. michahellis showed a more littoral distribution, less conditioned by the presence of elements like islands and favoring natural stations (Table 5). Following its generalist and opportunistic feeding behavior, this species favors areas with higher waterbird species richness, probably a clue to a greater diversity of foraging opportunities (including egg and chick predation or kleptoparasitism). Finally, *E. garzetta*, as a wading species, showed a negative response to distance to shore and a positive one to natural scrub habitats, either well-preserved (NDS) or slightly disturbed (NCS). The difference in vegetation cover between these two habitat types, however, does not necessarily indicate conservation status, but natural ecological character or successional stage. Thus, the landscape preferences of Little Egret include low plant cover habitats (saline steppe and open saltmarsh), although more concealed immediate shoreline areas also seem to be essential (dense scrub).

4.5. Management Implications

On the basis of our results, we can suggest three main management guidelines to enhance waterbird diversity and conservation value in Mediterranean coastal lagoons: (1) give effective protection and promote the restoration of well-preserved natural habitats around the lagoon,

emphasizing the maintenance of their structural continuity towards inland areas; (2) specifically reduce disturbance in the first band of nearshore waters, where several key indicator species converge; (3) combine the preservation and enhancement of the natural physiognomy of the shoreline, with the management of watershed impacts whose functional effects reach waterbirds via 'hidden pathways' (e.g., subsurface hydrological processes, lagoon trophic webs, etc.); and (4) take into account previous research on the role of natural habitat windows (salt marshes, saline steppes, reed beds), of proven value for nearshore waterbirds, for other relevant avian assemblages like steppe birds [30], searching for positive conservation synergies.

5. Conclusions

Unlike waterbird indices, the difficulty of implementing other biological indices (e.g., those based on benthos) in Mediterranean coastal lagoons is the high variability in the composition of species [37,43], making it difficult to extrapolate patterns and associations. In this regard, waterbird assemblages of Mediterranean coastal lagoons are more homogeneous and consistent among sites across relatively large geographical divisions (see Waterbird Population Estimates online database: http://wpe.wetlands.org/). Assuming that the same major environmental drivers, both natural (hydrological, geomorphological) and anthropogenic (agriculture, fishery management, urbanization), govern the functioning of Mediterranean CLs, we can expect waterbird species and communities to respond in a similar way. Long-term datasets provided by international waterbird censuses (IWC) in representative coastal lagoons are of the utmost important to perform comparative studies among sites subjected to varying degrees of disturbance. Given the effectiveness of such approach, the low consideration of the ornithological values in coastal lagoons in global assessments is surprising [9]. In this regard, this study highlights the importance of using waterbirds as bioindicators in semi-enclosed coastal systems by integrating the analysis of their role as indicators of the ecological status of the lagoon through the analysis of their variations in relation to food web ascending effects and their dependence on adjacent terrestrial natural habitats.

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