

Waterbirds and nutrient enrichment in Mar Menor Lagoon, a shallow coastal lake in southeast Spain

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Abstract

The Mar Menor, a 135-km² saline lake, is the largest water surface on the western Mediterranean coast, and an internationally important bird area. It is surrounded by a large irrigated agricultural plain, with dense tourism developments. Although the impacts of these activities on water quality are locally evident, their effects on waterbird populations are poorly known. In the winter 2004–2005, we studied the distribution of four waterbird species (*Podiceps cristatus*, *Podiceps nigricollis*, *Phalacrocorax carbo* and *Fulica atra*) around the main drainage channel that discharges into the lake, where it was feasible to infer spatial patterns of eutrophication (alongshore and shore centre) from previous environmental surveys. Waterbirds were counted along a stretch of undeveloped shoreline extending southwards from the channel outlet, in contiguous sections, and in bands parallel to the shoreline. Linear mixed models (LMM) indicated the population density increased only markedly for grebes (*Podiceps cristatus*, *Podiceps nigricollis*) and coot (*Fulica atra*) in littoral bands qualifying as eutrophic, but not an alongshore response, with their finescale alongshore distribution being apparently unrelated to nutrient sources. Considering the whole lake, however, the temporal trends and distribution of the wintering populations indicated that waterbirds respond numerically, in a guild-specific way, to nutrient inputs. Grebes and coot could be a useful ‘two-stage’ warning signal for potential problem areas affected by similar influences.

Key words

agricultural drainage, coastal lake, eutrophication, monitoring, wintering waterbirds.

INTRODUCTION

Lakes and wetlands experience strong pressures on their biodiversity and water quality (e.g. Maltby 1986; Gibbs 2000) due to strong human demands on their surrounding land, shoreline and littoral waters (Gopal 2003), ranging from typical land-based activities (agriculture) to shoreline or water-related activities (tourism, recreation, aquatic sports, fish and shellfish catch or culture, etc.). Mediterranean coastal aquatic ecosystems are among the more vulnerable systems in regard to such pressures, mainly because of the concentration of human activities and population along its shores (De Stefano 2004).

Waterbirds can help to signal changes in a range of wetlands and lakes (Noordhuis *et al.* 2002), as they can respond strongly to hydrological stresses, vegetation changes, salinity, turbidity, nutrient loads and contaminants (Adamus 1996). Recent studies also used waterbirds as target

organisms to compare wetland shoreline sections subjected to different land uses and development intensities (Traut & Hostetler 2004). In the Mar Menor Lagoon (Murcia, southeast Spain), some wintering waterbird species responded positively to nutrient inputs during a period of lake eutrophication (Martínez *et al.* 2005a), a relationship that was already suggested by earlier studies of the lake’s bird community (Hernández & Robledano 1997).

Although waterbird abundance generally responds to processes of nutrient increases (or decreases) in coastal and inland waters (Nilsson 1985; Raffaelli 1999; Noordhuis *et al.* 2002), their use as biological indicators has been questioned, mainly because of the lack of direct measurable responses to changing food resources or other limnological variables (Adamus 1996; Green & Figuerola 2003). Birds could respond positively or negatively to nutrient changes, for example, depending on the stage of nutrient loading or removal (Van Impe 1985; Hoyer & Canfield 1994; Raffaelli 1999; Van Eerden *et al.* 2005). Furthermore, these responses sometimes manifest themselves in species-specific manners (Rönkä *et al.* 2005).

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This study highlights changes in the abundance and distribution of waterbirds wintering in a coastal lake, at a local spatial scale, in response to organic pollution from agricultural and urban effluents. The density of the indicator birds is expected to change spatially with gradients (alongshore and shore centre) of decreasing influence from the relevant nutrient point sources. Given the general response of some waterbird populations to the global nutrient input into the lake (Martínez *et al.* 2005a), it was thought that this focal study could set the basis for detection of spatial changes in trophic status within the lake, monitoring the expected future water quality improvements from planned remediation measures (e.g. collection and/or treatment of agricultural and urban effluents). Based on this perspective, we conducted an intensive winter-bird survey, as a complement to the gathering of secondary data for modelling the lake and its watershed (see, e.g. Martínez *et al.* 2005b). This survey also is regarded as a baseline study against which to gauge the effects of future water quality improvements. The focus was on wintering species, as additional data (yearly census) are available for comparison and interpretation of the results.

METHODS

Study site and area description

The Mar Menor Lagoon is a 135-km² coastal shallow lake located in the southeast part of the Iberian Peninsula. It has a mean depth of 4 m, and is surrounded by an irrigated agricultural plain of 330 km² with dense urban developments (Esteve & Martínez 2003). The lake is separated from the Mediterranean Sea by a narrow sand strip almost completely reclaimed for tourism. The lake has the largest water surface area in the western Mediterranean coast, and a remarkable biodiversity and scientific value. It has been a Ramsar Site since 1994, and an EU Bird Specially Protected Area and Barcelona Convention's Specially Protected Area of Mediterranean Importance since 2001 (see official information on values and criteria for these designations at website: <http://www.carm.es/medioambiente/>).

The study area is a stretch of undeveloped shoreline of the inner side of the lake, with a total length of 4.12 km (Fig. 1), extending from the southern end of Los Alcázares Military Base (37°43'50"N, 0°50'40"W), to the northern limit of the tourist village of Punta Brava (37°41'50"N, 0°49'40"W). The Albuñón channel, a permanent artificial watercourse cutting the lowest reaches of the former *wadi* or *rambla* (Spanish name for ephemeral watercourse) flows near the northern end of the study area. This channel

drains a sub-basin surface of 633 km², representing more than half of the lake's watershed (1.200 km²), and accounting for 8.6% of the total estimated run-off entering the lake (Martínez *et al.* 2005b; M. F. Carreño, pers. comm., 2005). In addition to the main channel's water discharge, all the studied shoreline is affected by diffuse drainage reaching the lake through a reed bed in the northern section, and through a saline steppe and marshland (Carmolí wetland) in the southern part (between the Albuñón Channel and Punta Brava; see Fig. 1).

In addition to natural run-off, the Albuñón Channel collects drainage water from agricultural fields, as well as infrequent discharges (refuse water) from desalination plants and occasionally from sewage treatment plants. The total estimated yearly flow is 20 Hm³, and the water conductivity usually ranges between 8 and 11 mS cm⁻², representing a brackish water input into the hypersaline (33.6–46.2 p.s.u.) Mar Menor main water mass (Lloret *et al.* 2005). Freshwater inputs from other channels (Miranda and Miedo), diffuse drainage and below-ground seepages also reach the lake through different sections of the shoreline, but never as a continuous open watercourse like the Albuñón channel.

Bird count data

The adjacent waters were divided into four parallel bands located at different distances from the shore (0–50, 50–250, 250–500 and >500 m), and in five shoreline sections at varying distances from the channel outlet (four on the southern side; one on the northern side), resulting in 20 cells (i.e. bands × shore sections) used as bird recording units (Fig. 1). The outer limit of the fourth band was set at 1000 m, for the practical reason that birds could not be adequately identified beyond this limit. The shoreline length of bird counting sections varied between 508.5 and 1376.9 m (average = 825 ± 148 standard deviation), with surface area varying between 51.9 and 77.34 ha (average = 66.85 ± 5.14 standard deviation).

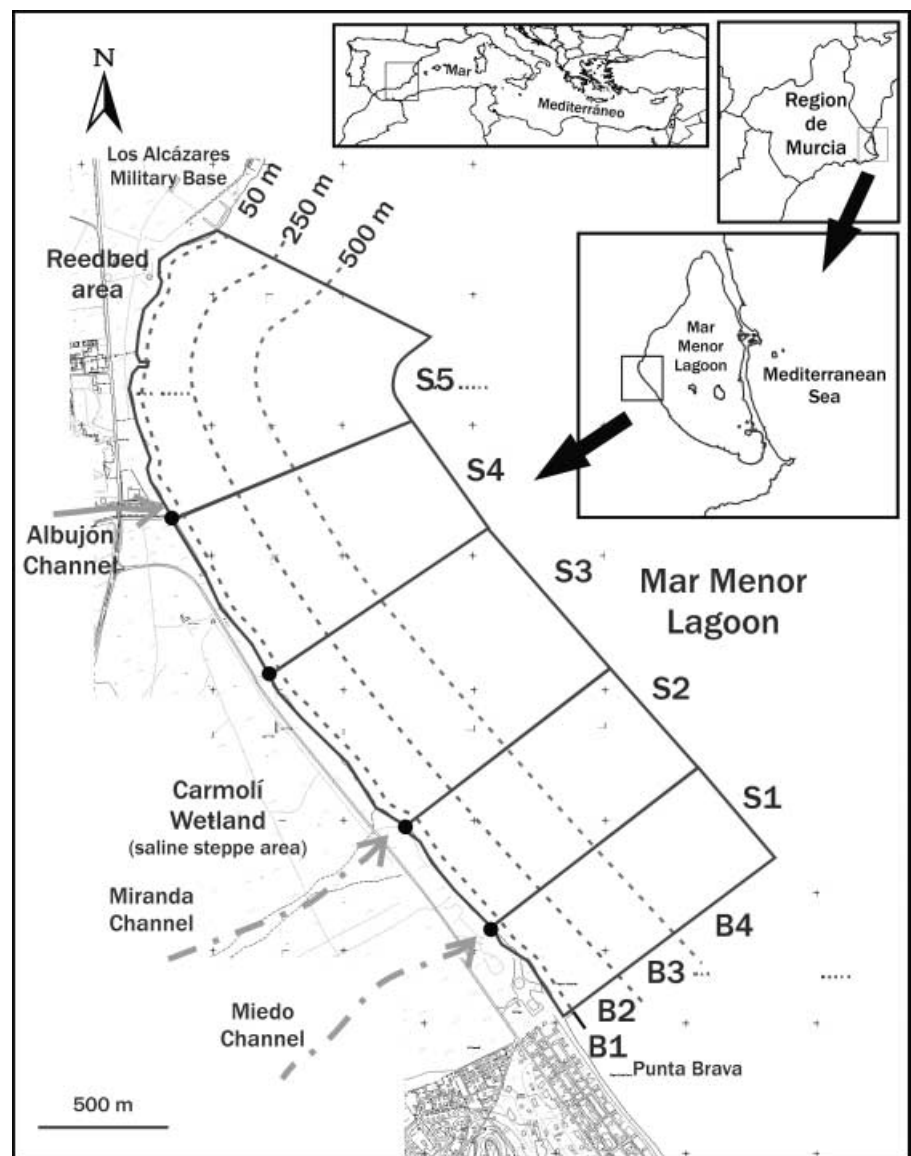
Units were recognized in the field through the use of several permanent visual references on land and in the water. The same observer (I.P.A.), who was previously trained in the estimation of distances on the basis of these references, did all the fieldwork. The differences in the size of the counting sections were mainly because of the need to ensure clearly recognizable boundaries.

Birds were counted weekly between October 2004 and March 2005, with a 15–60 × 90 spotting scope, from four points along the shoreline of the lake. This allowed full coverage of the five sections without significant disturbance (Fig. 1). The route could be completed in 2.5–3 h, within the first 4 h of daylight, and with the same sequence of

stops to minimize count variability. There were no signs of temporal changes in the distribution of the birds (moving along- or off-shore) that could parallel the temporal sequence of counts. Additional observations in the lake show that, in the absence of heavy distributions, there is very little change in the off-shore distribution of the species studied during the time interval when the counts were made. Four surveys were done each month, except in October and February when only three surveys could be completed. Although the observer recorded the birds' activity, most observations consisted of individual birds actively feeding or searching for food. Thus, the results have been assimilated to densities of feeding individuals. The most abundant wintering species were Eurasian coot (*Fulica atra*), black necked grebe (*Podiceps nigricollis*), and great crested grebe (*Podiceps cristatus*), with the first

two species previously found to be responding positively to nutrient enrichment at the site (Hernández & Robledano 1997; Martínez *et al.* 2005a). These three species account for a wide range of salinity tolerances, food preferences (from typically phytophagous to piscivorous), and feeding methods (from surface feeders to deep-water divers). To analyse the local spatial response of birds within the context of long-term changes of the lake's populations, the total count data of these species also were compiled from winter waterfowl census, in the framework of the International Waterbird Census (IWC) scheme (Hernández & Robledano 1991; Hernández *et al.* 2006; G. A. Ballesteros, pers. comm., 2006; Martínez *et al.* 2005a). These censuses are performed during a comprehensive boat survey covering the entire lake, and that followed the same route each year since the start of the scheme. Additional bird surveys

Fig. 1. Study area and bird recording units (counting cells) defined by sections (S1–S5) and bands (B1 = 0–50, B2 = 50–250, B3 = 250–500 and B4 = 500–1000 m). Black dots show the position of observation points along the shore.



(P. Farinós & F. Robledano, unpubl. data, 2006) were made in 14 different, 500 m-sections of the lake shore in the winter of 2005–2006. The eight sections of the internal shore (see Fig. 5) were used to evaluate changes in bird density at a larger scale within the lake. These sections could be ranked (e.g. see Bryce *et al.* 2002) depending on the qualitative evaluation of the two main stressors under study; namely, nutrient and freshwater inputs.

Nutrient and other biophysical parameters

Nutrient and other environmental data indicative of eutrophication gradients were obtained from several sources, as summarized in Table 1. The general nutrient patterns in the lake have been studied by Pérez-Ruzafa *et al.* (2002), and García Pintado *et al.* (2007) provided a characterization of the nutrient sources to the main input channels. Nevertheless, detailed measurements depicting shoreline gradients (other than those summarized here) are lacking. Temporal changes in the total nutrient loads into the lagoon were estimated in the framework of the DITTY Project (J. Martínez, unpubl. data, 2005).

Data analyses

Bird counts were expressed as densities (birds per hectare) in each counting cell, for each day of the census individually, and also averaged by month and for the entire winter season. This approach allowed analysis of spatial and temporal changes in bird abundance, and their

interpretation with respect to the main freshwater and nutrient discharges (Albujón Channel). It also allowed for the analysis of the influence of other physical and hydrological features of the lake and its surrounding wetlands.

Log-transformed daily density values of each bird species were analysed using linear-mixed models (LMM). To avoid temporal pseudoreplication, the sampling unit (cell) was included in the models as a random effect. The rest of the variables were considered as fixed factors, including band (distance from the shore), sector (along the shore), time (day, with October 1 = 1) and distance (from the channel mouth to the centre of each cell). The statistical significance of these factors was assessed by means of likelihood ratio tests (Venables & Ripley 2002), using the freely distributed 'R' software, available at <http://www.R-project.org/> (R Development Core Team 2006).

RESULTS

Nutrient and other biophysical parameters

The maximum nitrate concentration in the southern channels (discharging in sections 1–3) is about half of that recorded in the main effluent. Furthermore, the water flow in the channels, which usually seeps through the peripheral wetland, is four times lower. The nitrate concentration decreases rapidly (by 1–2 orders of magnitude) from the main channel mouth towards the centre of the lake. Fish

Table 1. Values of parameters selected as indicative of spatial eutrophication gradients in the study area (mean values or ranges reported for the winter months of 2002–2006 have been assigned to the studied bands or sections. Values expressed in $\mu\text{mol L}^{-1}$ have been converted to mg L^{-1} where necessary to allow direct comparisons. Miranda and Miedo channels seep underground before reaching the lake. The values are from the nearest watered sampling sites. The data are extracted from various sources (in brackets): (1) Martínez *et al.* 2005a; (2) Jiménez-Cárceles *et al.* 2005; (3) Lloret *et al.* 2005; (4) DITTY Project 2005–2006 (unpublished); (5) Velasco *et al.* 2006; (6) Verdiell *et al.* 2007)

Variable:	Location					
	Band 1 (Outlet)	Section 5/4 (Albujón channel)		Lake centre	Section 3/2 (Miranda channel)	Section 2/1 (Miedo channel)
Nitrate concentration (mg L^{-1})	62.0 (1)	Band 3 0.41 (3)	Band 4 3.41 (3)	0.81 (3)	Band 1 (Outlet) 5.4–33.1 (1.2)	Band 1 (Outlet) 17.74–24.02 (2)
Mean flow (L s^{-1})		Band 1 (Outlet) 127.0 (4)			Band 1 (Outlet) 38.15 (5)	Band 1 (Outlet) 36.28 (5)
<i>Mugilidae</i> density (CPUE) in shallow littoral zones		Section 5/4 Band 1 (Outlet) 26.1 (6)			Section 3 to 1 Band 1 (Outlet) 2.0 (6)	
<i>Mugilidae</i> biomass (WPUE) in shallow littoral zones		114.5 (6)			9.7 (6)	

CPUE, catch per unit effort; WPUE, weight per unit effort.

abundance (density and biomass of Mugilidae, see Table 1) is also rapidly reduced alongshore (Table 1), indicating that the productivity available to birds decreases in both dimensions, as do the nutrient concentrations.

Waterbirds

The coot was the most abundant species, while the great crested grebe was slightly more abundant than the black necked grebe (Table 2). Coot attained its greatest abundance in November, and had stabilized at slightly lower numbers by January. The two species of grebe exhibited a steady increase from October, reaching a peak in January to February (Fig. 2).

Figure 3 illustrates the distribution of mean winter density in the study area for the three waterbird species. For all the species, S4 and S2 were the preferred sections. Although minor monthly changes in their distributions were detected in all species, there was a general spatial preference of coot for the cells of S4 closest to the outlet,

and of great crested grebe for S2, overriding temporal shifts from one another in both species.

The coot was virtually restricted to the first band, with its density peaking in section 2 just to the south of the main discharge (Albujón channel). This was partially shown by the significance of the model, including band effects, while the effects of section were not significant (Table 3, Fig. 4). Great crested grebe also reached their greater densities in the first band, although with much lower values than coot. However, they were also present in the second band. Both species exhibited maximum densities in section 2. Again, only 'band', but not 'section', showed significant effects on density (Table 3). Black necked grebe had the lowest mean density and was the most evenly distributed species, although a bimodal pattern appeared, with peaks in sections 4 and 2. The pattern of usage $B1 > B2$ held for all the study period in most sections. As in the former species 'band', but not 'section', had a significant effect on density (Table 3).

Table 2. Mean count (MC \pm standard error, SE) for October to March, monthly counts (total and mean) and estimates of bird use (U, total bird days) for three most abundant waterbird species in the study area (gross densities (GD [birds/ha] \pm standard error, SE) for the whole lake were calculated from mean winter waterfowl census of the years 2000–2005, unpublished data)

		All winter	October	November	December	January	February	March
Coot	MC (\pm SE)	444.95 (34.04)	206.00 (66.95)	600.00 (73.37)	519.75 (25.85)	518.50 (29.58)	461.33 (61.33)	308.50 (36.83)
	U	79 052.49	6386.00	18 000.00	16 112.25	16 073.50	12 917.24	9563.50
	GD (\pm SE)	0.023 (0.005)						
<i>F. atra</i>	MC (\pm SE)	46.27 (5.71)	34.00 (1.73)	35.50 (12.65)	38.50 (14.60)	46.75 (15.64)	71.00 (23.81)	55.00 (8.69)
	U	8454.75	1054	1065	1193.5	1449.25	1988	1705
	GD (\pm SE)	0.01 (0.008)						
Black-necked grebe <i>P. nigricollis</i>	MC (\pm SE)	60.85 (4.69)	21.00 (1.52)	23.25 (5.76)	45.50 (6.19)	101.75 (18.75)	105.33 (42.00)	68.25 (20.29)
	U	10 978.24	651	697.5	1410.5	3154.25	2949.24	2115.75
	GD (\pm SE)	0.03 (0.002)						
Great crested grebe <i>P. cristatus</i>	MC (\pm SE)	551.86 (37.45)	261.00 (65.36)	658.75 (80.40)	603.75 (29.51)	667.00 (13.50)	637.66 (105.04)	431.75 (43.67)
	U	98 485.48	8091	19 762.5	18 716.25	20 677	17 854.48	13 384.25
	GD (\pm SE)							
Total	MC (\pm SE)	551.86 (37.45)	261.00 (65.36)	658.75 (80.40)	603.75 (29.51)	667.00 (13.50)	637.66 (105.04)	431.75 (43.67)
	U	98 485.48	8091	19 762.5	18 716.25	20 677	17 854.48	13 384.25

The additional surveys made in the winter of 2005–2006 indicated peak winter concentrations of coot in S4 (=study area), and of grebes in sections much further south (S6 for great crested grebe; S6–S7 for black-necked grebe). Both species also had secondary peaks in S4 (Fig. 5).

For all the species, the January census indicated a marked increase in wintering numbers throughout the Mar Menor (Fig. 6). Grebes increased after 1986, while coot did not so until 1992. There was a decline in all species after 1995. The wintering population of grebes and coot exhibited an increasing trend from 2000. Coot was recorded for the first time in 1991, increasing up to >600 birds in 2005 (Fig. 6).

The average of IWCs made between 1990 and 2005 represents 80% of the total coot wintering in the Mar Menor. Although data on wintering grebes usually are not reported separately from the rest of the lake, recent counts (winter 2005–2006) indicate that at least 19.6% of the total wintering great crested grebes, and 15.1% of the black-necked grebes, concentrated around the Albuñón channel outlet. The peak concentrations occur further south for both species, in areas much less affected by agricultural drainage or wastewater discharge.

DISCUSSION

Waterbirds respond locally to the main spatial and environmental gradients of nutrient discharges into the

Mar Menor Lagoon. This response occurs at different spatial (whole lake/study area) and temporal (long/short-term) scales. Although the data gathered on nutrient inputs and other biophysical variables only allowed a qualitative ranking of sections and sites (e.g. see Bryce *et al.* 2002), the main productivity gradients are generally associated with changes in bird distribution and density, allowing the incorporation of waterbirds into the process of biomonitoring (Brazner *et al.* 2007).

Nutrient loads affect birds differentially, depending on the environmental characteristics or resources (e.g. abundance or detectability of preferred food; salinity) selected by each species or guild, such as herbivores (coot) versus fish and invertebrate feeders (grebes), dabblers/surface feeders (coot) versus divers (grebes), etc. Thus, it is important to identify the scale at which waterbird populations and assemblages respond to eutrophication. The changes in waterbird numbers are consistent with a general response to processes of nutrient increases in coastal and inland waters (Nilsson 1985; Raffaelli 1999), like other populations that respond either positively or negatively to the stage of nutrient loading or removal (Van Impe 1985; Hoyer & Canfield 1994; Raffaelli 1999; Van Eerden *et al.* 2005). The three species considered in this study experienced a marked increase in their total wintering numbers, although with different patterns (Fig. 6),

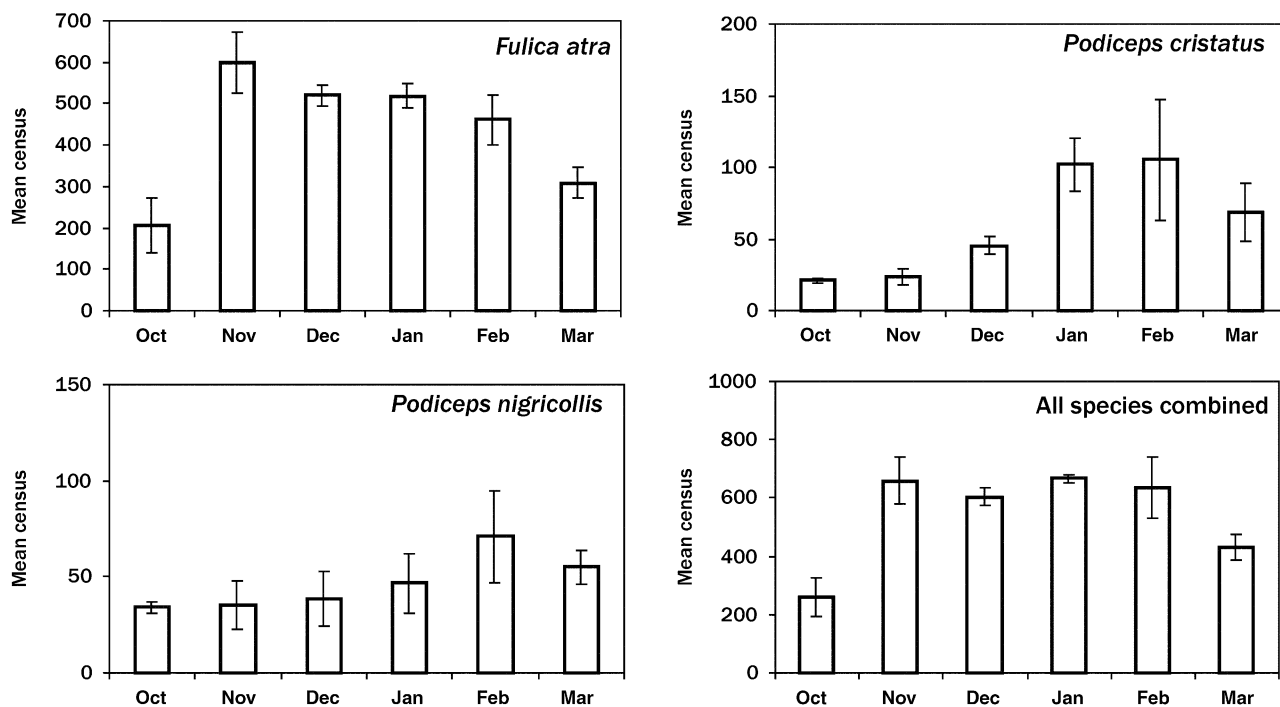


Fig. 2. Changes in mean monthly census of the three waterbird species in study area (Bars represent the mean value (\pm standard error) of all census for each month; $N = 4$ census, except in February).

indicating such species-specific, or at least guild-specific, responses (Rönkä *et al.* 2005), which also is illustrated by the time lag between the main period of increases in grebes and coots.

Previous studies of waterbird responses to eutrophication at this site (Martínez *et al.* 2005a) confirmed a good match between piscivore abundance and the estimated nitrogen load reaching the lake, except during phases of very high nutrient inputs, when blooming jellyfish could control the planktonic food web (Pérez-Ruzafa *et al.* 2002). The

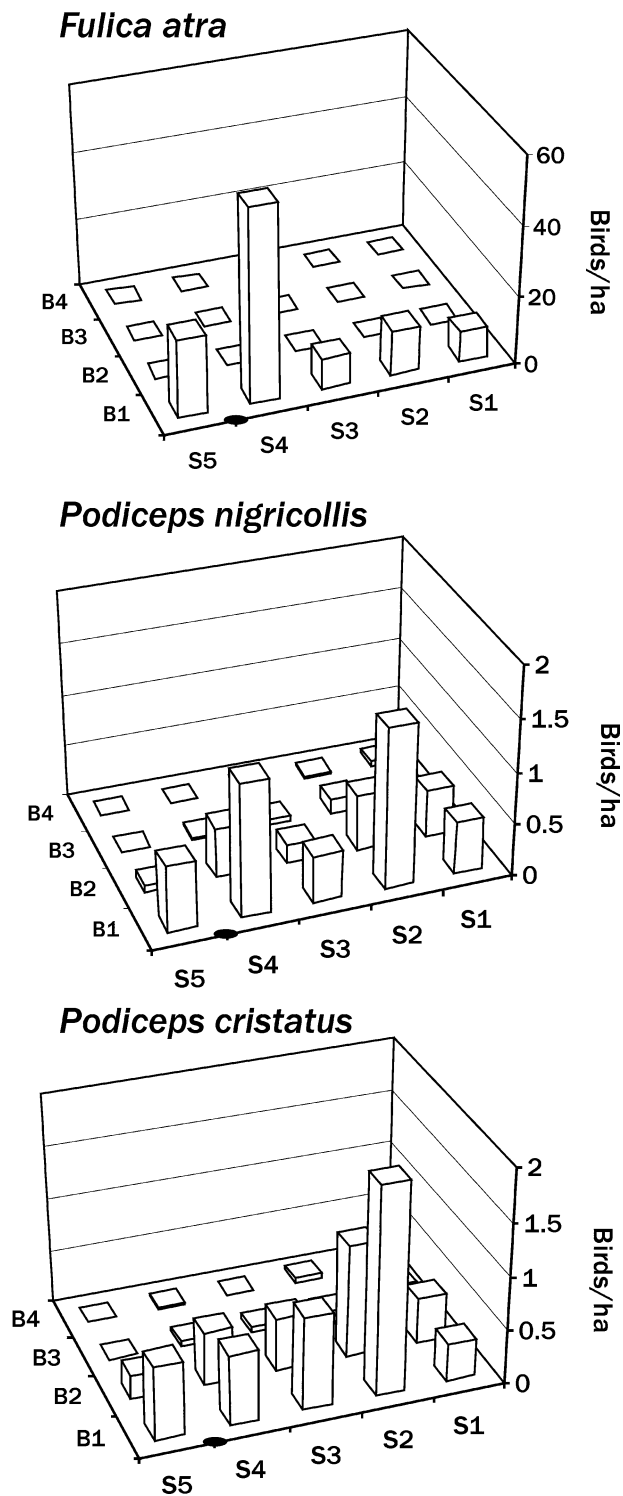


Fig. 3. Spatial variation of the winter mean density of three most abundant waterbird species in study area.

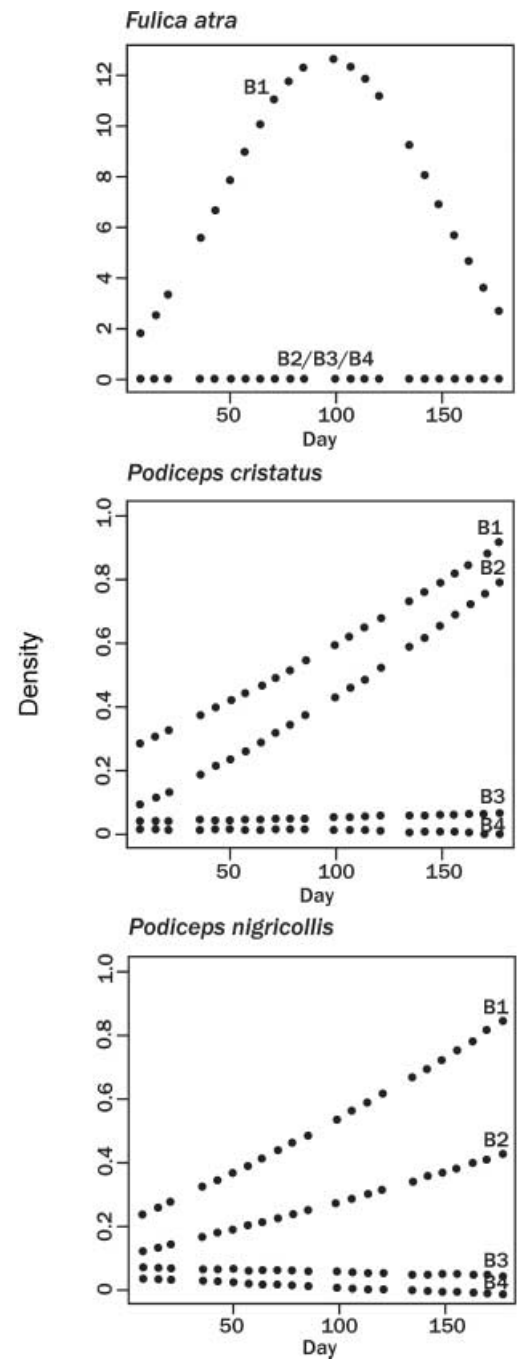


Fig. 4. Plots of the linear mixed models of three most abundant waterbird species, showing the predicted relationship of bird density with band through time (day).

numbers of grebes increased from the late 1980s, to reach high values during the first half of the 1990s. After a decrease-fluctuating phase by the end of the century, the abundance of this waterbird guild again increased, in the case of black-necked grebe, to reach maximum numbers in 2003. Jellyfish blooms are a possible explanation for the lack of waterbird responses to nutrient loads in some years. Under anthropogenic nutrient enrichment, gelatinous plankton is known to interact with fish (Vasas *et al.* 2007) and could reduce the prey available to fish-eating birds. Alternative explanations for this lack of response are external factors, such as the conditions in other wetlands, or the status of waterbird populations at wider scales (Spanish or European). National or European IWC results can be used as indexes of general population or habitat conditions. Previous research (e.g. Martínez *et al.* 2005a) indicated that the trends of the two grebe species wintering in the Mar Menor do not match those of the Spanish population. When compared to European population indices (Wetlands International 2006), it also is found that local fluctuations in recent years depart from general

increasing trends, with local trophic interactions being the most plausible explanation.

Although the numerical trend of coot wintering in the Mar Menor is similar to that for the Murcia Region's reservoirs (whose catchments also are affected by eutrophication), it differs from the populations wintering in Europe (moderately declining; Birdlife International 2004), in Spain as a whole (stable; Martí & Del Moral 2003), and in the neighbouring Valencian community (dramatically declining; Gimenez 2004). At the European scale, after a phase of increase, wintering coot are now decreasing, as a consequence of changes in the trends of agricultural-driven fertilization of coastal waters (Van Eerden *et al.* 2005).

At a fine spatial and temporal scale, the three waterbird species use waters (first two bands) that can be classified as eutrophic, while the farthest two bands are still oligotrophic (Lloret *et al.* 2005; Martínez *et al.* 2005a). This association is the only significant spatial effect depicted by the models, and the only that would support a direct indicator response. The expected decrease in density

Table 3. Results of single and multiple linear mixed models of waterbird density against time (day), band (1–4) and section (1–5), and their interactions

Species	Model	d.f.	AIC	Log-likelihood	Test	χ^2	<i>P</i>
Coot	Null	2	1434.83	-715.415			
	Random effects	3	946.41	-470.206	1 vs 2	490.420	<0.0001
	Time	4	948.15	-470.079	2 vs 3	0.253	0.6149
	Time + time ²	5	934.98	-462.492	2 vs 4	15.427	0.0004
	Sect	7	952.85	-469.425	2 vs 5	1.661	0.8159
	Band	6	927.08	-457.540	2 vs 6	25.332	<0.0001
	Band + time + time ²	8	915.65	-449.826	6 vs 9	15.427	<0.0001
	Band * (time + time ²)	11	876.75	-424.377	9 vs 10	50.900	<0.0001
Great crested grebe	Null	2	389.86	-192.932			
	Random effects	3	297.68	-145.841	1 vs 2	94.183	<0.0001
	Time	4	278.98	-135.492	2 vs 3	20.697	<0.0001
	Time + time ²	5	277.88	-133.942	3 vs 4	3.099	0.0783
	Sect	7	303.56	-144.778	2 vs 5	2.125	0.7127
	Band	6	269.87	-128.934	2 vs 6	33.812	<0.0001
	Band + time + time ²	8	269.87	-128.934	2 vs 6	33.812	<0.0001
Black necked grebe	Null	2	366.58	-181.290			
	Random effects	3	300.92	-147.462	1 vs 2	67.656	<0.0001
	Time	4	295.02	-143.510	2 vs 3	7.904	0.0049
	Time + time ²	5	293.95	-141.973	3 vs 4	3.072	0.0796
	Sect	7	305.86	-145.929	2 vs 5	3.067	0.5471
	Band	6	278.50	-133.248	2 vs 6	28.426	<0.0001
	Band + time + time ²	7	272.59	-129.296	6 vs 9	36.330	<0.0001
	Band * (time + time ²)	10	264.79	-122.396	9 vs 10	13.802	0.0032

AIC, Akaike Information Criterion.

alongshore with distance from the main nutrient source (Albuñón channel) was not identified by the models, which did not reveal any other pattern of change. The distribution of the birds, however, could not be conditioned by nutrient status or productivity, but reflect simply the species ecological or behavioural preferences in the shore-centre gradient (dictated by swimming capabilities, foraging depth, sensitivity to disturbance).

Waterbirds were not systematically surveyed in the winter 2004–2005 in the nearby sections of the shoreline (on both sides), mainly because previous surveys indicated that the densities of the species studied were much lower in those locations. This situation could simply be a consequence of the artificial nature of these nearby areas. A natural shoreline stretch could act as a general cue for habitat selection at the landscape scale (Taft & Haig 2006),

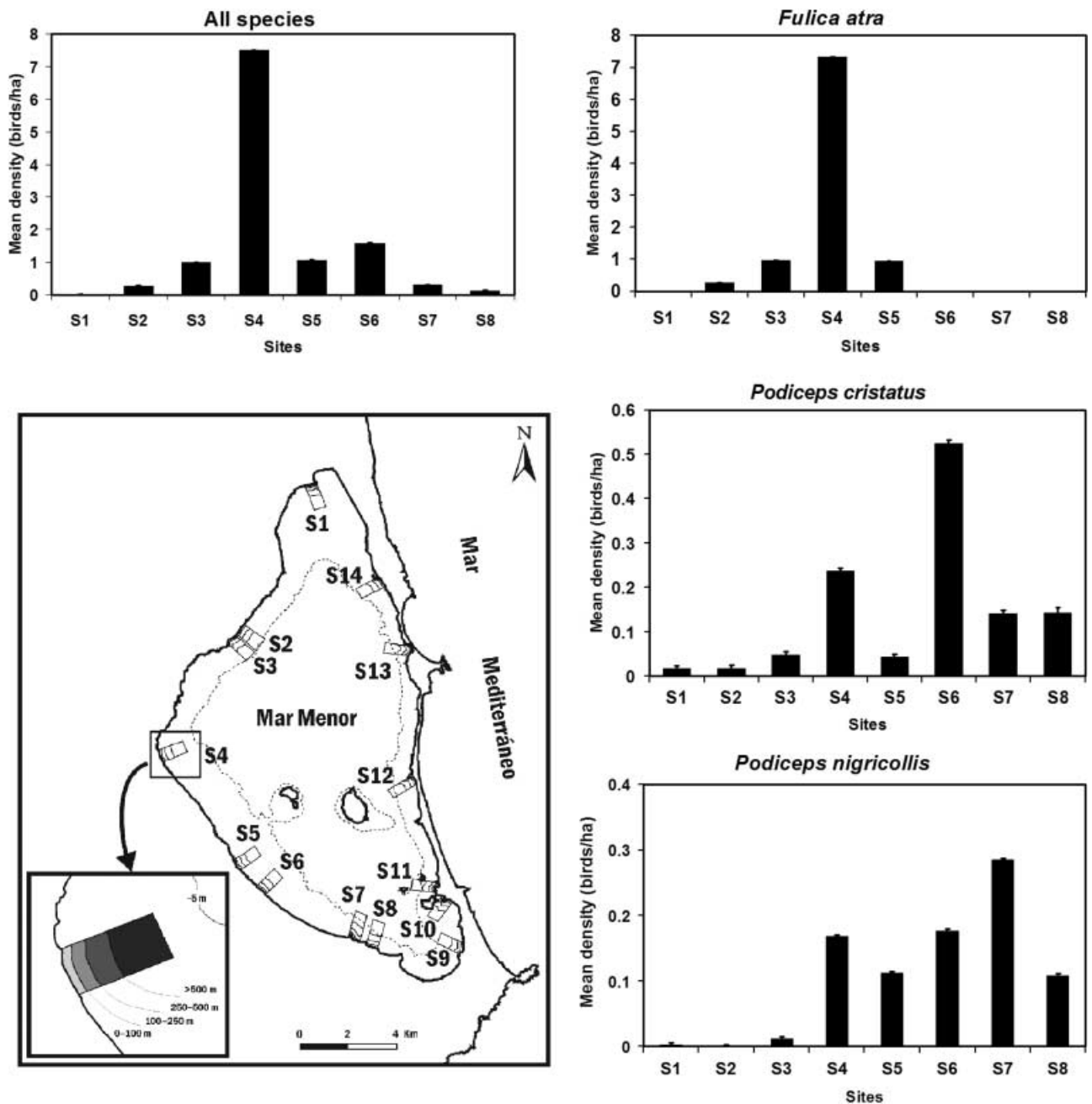


Fig. 5. Winter abundances of the waterbird species in study area (average densities \pm standard error from counts made between December 2005 and March 2006) in different sections of the lakeshore affected by freshwater and nutrient inputs (see map; S1 and S8 have no input channels or seepages; nutrient inputs can be qualitatively ranked S4 >> S2,S3,S5 > S6,S7, and freshwater inputs S4 > S2 > S3,S5 S6,S7).

with the trophic value being a secondary factor. The effect of productivity gradients on birds therefore can be more apparent in comparisons with other natural sections, than in within-section analysis.

Additional surveys in the winter of 2005–2006 detected peak winter concentrations of grebes in sections much further south (Fig. 5), suggesting that, at the lake scale, these species could favour less-eutrophic waters. This is in accordance with their earlier response to the increased nutrient discharge into the lake (Martínez *et al.* 2005a). Coot continued to peak near the Albuñón channel outlet (the studied sections), however, with smaller numbers being found around minor freshwater discharges that do not receive raw sewage and which drain less intensive agricultural areas. The full gradient of nutrient concentrations to which the waterbirds respond seems to extend to the whole lake, with coot apparently peaking under more eutrophic conditions, and grebes at intermediate ones. The total bird abundance, however, increased markedly in the most productive waters (Fig. 5).

Secondary freshwater inputs also could be important in the study area, especially for the less salt-tolerant species (Jehl 2005), as a source of drinking water (but also see Mahoney & Jehl 1985). This factor, as well as feeding habits, could explain the differences in the band distribution between coot and grebes, with the coot tied to the closest ones. Unfortunately, detailed data on spatial salinity changes along the studied gradients are lacking. The effects of reduced salinity can be confounded with those of increased nutrient inputs, as both are generally spatially associated. Most nutrients reach the lagoon via freshwater currents. However, the disproportionate

abundance of coot around the Albuñón outlet (the main nutrient source) suggests a trophic attraction as the main explanatory factor (Fig. 5). In fact, coot are absent from the freshwater inputs that contain lower nutrient loads (S6, S7), and the black-necked grebe, a high salinity-tolerant species (Mahoney & Jehl 1985), is relatively abundant in the freshest site (the study area, or S4). Although salinity reduction can be locally important, the effects of freshwater inputs *per se* will not be evident until nutrients are removed from the main incoming currents.

Coot are restricted to the first littoral band, where light and nutrient conditions promote the seasonal development of floating algae (Taylor *et al.* 2001), and where there is access to other food resources (e.g. *Phragmites* seeds). Coot densities in the cells of the first band are higher than those reported for brackish coastal wetlands of southeast Spain with dense *Ruppia* meadows (F. Robledano, unpubl. data, 1992). For piscivores (grebes), the shallow waters close to the shore and the channel outlets also are recognized as fish-rich areas, as a result of the positive effects of freshwater inputs in the development of animal and plant food resources, and in the creation of microhabitats and refuge areas (Pérez-Ruzafa *et al.* 2004; Verdiell *et al.*, 2007).

Other effects of food resources on habitat preferences are more difficult to establish. As a rule, however, the three waterbird species become rare in the areas dominated by *Caulerpa prolifera* meadows (outer bands), which is characteristic of an oligotrophic status and poor in fish resources. The feeding activity of great crested grebes in eutrophic waters has been shown to be limited by such factors as underwater visibility, exploitable fish biomass, fish size, and vertical distribution of prey (Van Eerden

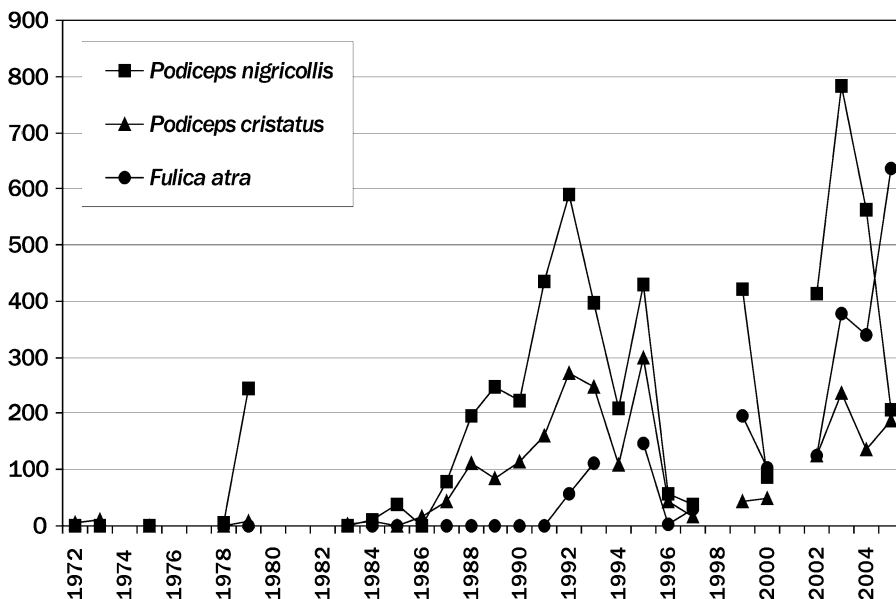


Fig. 6. Changes in the wintering populations (January census) of the three waterbird species in study area.

et al. 2003). Considering these factors, the preference for more productive waters close to the shore, which are rich in juvenile and small fish prey and, in our case, not limited by visibility, is justified, provided that the development of filamentous algae does not interfere with feeding activity. These relationships, however, require further investigation.

The study findings support our impression that the influence of nutrient inputs cannot be ruled out as the main factor that explains local waterbird distribution, although the birds are probably responding to a general eutrophic status of these littoral waters, rather than exhibiting a spatial response to the local gradients created by major point discharges. That the sections located farther from the Albuñón channel are used on average by waterbirds similarly than the closest ones, suggests that secondary discharges (Miedo and Miranda channels) also might be important for birds. This is in addition to the southward transport of nutrients because of the main N-S circulation pattern along this section of the lake (Pérez-Ruzafa *et al.* 2005). These local processes could buffer differences in the productivity of the resources exploited by waterbirds. As a result, their fine-scale alongshore distribution seems apparently unrelated to nutrient sources. Direct observations indicate that the closest cells of all sections have a similar development of filamentous algae and detritus, the food preferred by coot during the winter (Perrow *et al.* 1997). Under these trophic conditions, herbivorous waterbirds do not seem able to discriminate between sections, provided that landscape characteristics and habitat structure are suited to their ecology. Although there are marked differences in juvenile fish density and biomass along the shore (Table 1; Verdiell *et al.*, 2007), these data refer to the shallowest shoreline portion, areas that are densely covered by algae and act as a nursery area for fish. It is possible that fish biomass exported to contiguous waters (available to grebes) tends to a more homogeneous distribution.

It appears that enough food resources for piscivorous have developed in the lake before the biomass of algae and other plant food species exceeded the threshold to allow herbivores to settle. Thus, the increase of piscivores can be interpreted as an initial warning signal of eutrophication in littoral waters around nutrient discharge points that, when followed by the appearance of herbivores in the same area, provide a warning about a more radical change in the waters close to these nutrient sources. The association of grebes and coots with drainage-affected areas (rather than with particular point sources of nutrients), and particularly with littoral waters within these areas, supports an indicator value regarding water quality surveillance, although this value can be reduced by a non-linear response to

continued nutrient enrichment. The existence of different spatial and temporal scales in the response of waterbirds guilds to the symptoms of eutrophication enhances their performance, not only as 'early warning' signs, but also as 'two stage' indicators of great value for wetland managers (Raffaelli 1999; Lemly & King 2000).

As birds are easy and inexpensive to monitor (Gregory *et al.* 2005), ongoing waterbird census schemes for wetland evaluation must be reinforced, and can be integrated into biological surveillance programmes. Bird data provided by these schemes supported more than a decade ago the inclusion of the whole Mar Menor complex in the Ramsar List and, more recently, its designation as EU Bird SPA. Although none of the three *indicator* species utilized in this study satisfies the numerical criteria for these designations, they contribute to the overall bird abundance and diversity. But it can be argued that the populations of some waterbird species that satisfy numerical criteria (e.g. black-winged stilt *Himantopus himantopus*, little egret *Egretta garzetta*), in fact, could have responded to direct or indirect effects of the agriculture-driven changes in the structure and functioning of the lake system. This finding connects water quality and biodiversity objectives, since achievement of the first through nutrient removal could be detrimental for birds, as the available food resources would be reduced (Van Impe 1985; Van Eerden *et al.* 2005), reversing the positive trends of the early stages of nutrient enrichment. This situation also applies to salinity reduction, whose consequences can be favourable for bird species diversity, but detrimental for the lake ecological system. However, as Rönkä *et al.* (2005) have shown, eutrophication could hamper birds over the long term, by negatively affecting food webs and feeding habitat. Moreover, bird richness and density of moderately eutrophic or freshened lake stages do not necessarily represent the high integrity conditions of undisturbed 'reference' stages (Bryce *et al.* 2002).

In any case, these study results are only approximately indicative of the fine-scale relationships between waterbirds and nutrient loadings. There are still important gaps in our knowledge of the food relationships involving birds in the Mar Menor. The potential for incorporating waterbirds into Decision Support Systems (Martínez *et al.* 2005a), however, support a greater continuity and intensity in the monitoring task, with at least monthly census in representative sections, coupled with less-frequent intensive sampling campaigns of environmental variables.

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REFERENCES

- Adamus P. R. (1996) *Bioindicators for Assessing Ecological Integrity of Prairie Wetlands*. EPA/600/R-96/082. US Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oregon.
- Birdlife International. (2004) *Birds in Europe: Population Estimates, Trends and Conservation Status*. Birdlife International (Birdlife Conservation Series No 12), Cambridge, UK.
- Brazner J. C., Danz N. P., Niemi G. J. *et al.* (2007) Evaluation of geographic, geomorphic and human influences on Great Lakes wetland indicators: A multi-assembly approach. *Ecol. Indic.* **7**, 610–35.
- Bryce S. A., Hughes R. M. & Kaufmann P. R. (2002) Development of a bird integrity index: Using bird assemblages as indicators of riparian condition. *Environ. Manage.* **30**, 294–310.
- De Stefano L. (2004) *Freshwater and Tourism in the Mediterranean*. WWF Mediterranean Program, Rome. Available from <http://assets.panda.org/downloads/medpotourismreportfinal.html>. Accessed on 26 May 2006.
- Esteve M. A. & Martínez J. (2003) *Mar Menor-Spain*. DITTY Project. EC 'Energy, Environment and Sustainable Development Programme' Available from <http://www.dittyproject.org/MarMenor.asp>. Accessed on 5 May 2006.
- García Pintado J., Martínez Mena M., Barberá G. G., Alvadalejo J. & Castillo V. (2007) Anthropogenic nutrient sources and loads from a Mediterranean catchment into a coastal lagoon: Mar Menor, Spain. *Sci. Total Environ.* **373**, 220–39.
- Gibbs J. P. (2000) Wetland loss and biodiversity conservation. *Conserv. Biol.* **14**, 314–7.
- Gimenez M. (2004) La Focha Común no se podrá cazar en la Comunidad Valenciana. *La Garcilla* **120**, 41.
- Gopal B. (2003) Perspectives on wetland science, application and policy. *Hydrobiologia* **490**, 1–10.
- Green A. J. & Figuerola J. (2003) Aves acuáticas como bioindicadores en los humedales. In: *Ecología, Manejo y Conservación de Los Humedales* (eds M. Paracuellos & J. J. Casas). Instituto de Estudios Almerienses, Almería, Spain. Available from <http://i2.dipalme.org/Servicios/Municipios/pueblos.nsf/iealmerienses.html>. Accessed on 5 June 2006.
- Gregory R. D., Van Strien A. J., Vorisek P. *et al.* (2005) Developing indicators for European birds. *Phil. Trans. R. Soc. B.* **360**, 269–88.
- Hernández A. J., Fernández-Caro A. & Ibáñez J. M. (2006) *Censo Invernal 2005 de Acuáticas de la Región de Murcia*. El Naturalista Digital (<http://www.asociacionanse.org/naturalista-digital>). Asociación de Naturalistas del Sureste, Murcia, Spain.
- Hernández V. & Robledano F. (1991) Censos invernales de aves acuáticas en la Región de Murcia, SE de España (1972–90). *An. Biol. (Biol. Anim.)* **17**, 71–83.
- Hernández V. & Robledano F. (1997) La comunidad de aves acuáticas del Mar Menor (Murcia, SE España): Aproximación a su respuesta a las modificaciones ambientales en La Laguna. In: *Actas XII Jornadas Ornitológicas Españolas*. Instituto de Estudios Almerienses, Almería, Spain. Available from <http://i2.dipalme.org/Servicios/Municipios/pueblos.nsf/iealmerienses.html>. Accessed on 5 June 2006.
- Hoyer M. V. & Canfield D. E. (1994) Bird abundance and species richness on Florida lakes: Influence of trophic status, lake morphology, and aquatic macrophytes. *Hydrobiologia* **297/280**, 107–19.
- Jehl J. R. (2005) Gadwall biology in a hypersaline environment: Is high productivity offset by postbreeding mortality? *Waterbirds* **28**, 335–43.
- Jiménez-Cárceles F. J., Alvarez-Rogel J. & Egea-Nicolás C. (2005) Depuración de aguas eutrofizadas en un humedal natural costero del Sureste de España. In: *Encuentro Internacional en Fitodepuración – International Meeting on Phytodepuration*. Fundación Global Nature, Lorca, Spain. Available from www.macrophytes.info/Documentos-Encuentro%Internacional.htm. Accessed on 5 May 2006.
- Lemly A. D. & King R. S. (2000) An insect-bacteria bioindicator for assessing detrimental nutrient enrichment in wetlands. *Wetlands* **20**, 91–100.
- Lloret J., Marín A., Marín-Guirao L. & Velasco J. (2005) Changes in macrophytes distribution in a hypersaline coastal lagoon associated with the development of intensively irrigated agriculture. *Ocean Coast. Manag.* **48**, 828–42.
- Mahoney S. A. & Jehl J. R. (1985) Avoidance of salt-loading by a diving bird at a hypersaline and alkaline lake: Eared grebe. *Condor* **87**, 389–97.
- Maltby E. (1986) *Waterlogged Wealth*. Earthscan, London.
- Martí R. & Del Moral J. C. (eds) (2003) *La Invernada*

- de aves Acuáticas en España*. Dirección General de Conservación de la Naturaleza-SEO/Birdlife. Ed. Organismo Autónomo Parques Nacionales. Ministerio de Medio Ambiente, Madrid, Spain.
- Martínez J., Esteve M. A., Robledano F., Pardo M. T. & Carreño M. F. (2005a) Aquatic birds as bioindicators of trophic changes and ecosystem deterioration in the Mar Menor lagoon (SE Spain). *Hydrobiologia* **550**, 221–35.
- Martínez J. F., Alonso F., Carreño F., Pardo M. T., Miñano J. & Esteve M. A. (2005b) *Report on Watershed Modelling in Mar Menor Site*. DITTY Project. EC 'Energy, Environment and Sustainable Development Programme'. Available from <http://www.dittyproject.org/MarMenor.asp>. Accessed on 5 May 2006.
- Nilsson L. (1985) Bestandsdichte und Vergesellschaftung brütender Wasservögel Südschwedens in Beziehung zur Produktivität der Seen. *J. Ornithol.* **126**, 85–92.
- Noordhuis R., van der Molen D. T. & van der Berg M. S. (2002) Response of herbivorous water-birds to the return of *Chara* in Lake Veluwemeer, The Netherlands. *Aquat. Bot.* **72**, 349–67.
- Pérez-Ruzafa A., Gilabert J., Gutierrez J. M., Fernández A. I., Marcos C. & Sabah S. (2002) Evidence of a planktonic food web response to changes in nutrient input dynamics in the Mar Menor coastal lagoon, Spain. *Hydrobiologia* **475/476**, 359–69.
- Pérez-Ruzafa A., Quispe J. I., García-Charton J. A. & Marcos C. (2004) Composition, structure and distribution of the ichthyoplankton in a Mediterranean coastal lagoon. *J. Fish Biol.* **64**, 202–18.
- Pérez-Ruzafa A., Fernández A. I., Marcos C., Gilabert J., Quispe J. I. & García-Charton J. A. (2005) Spatial and temporal variations of hydrological conditions, nutrients and chlorophyll *a* in a Mediterranean coastal lagoon (Mar Menor, Spain). *Hydrobiologia* **550**, 11–27.
- Perrow M. R., Schutten J. H., Howes J. R., Holzer T., Madgwick F. J. & Jowitt A. J. D. (1997) Interactions between coot (*Fulica atra*) and submerged macrophytes: The role of birds in the restoration process. *Hydrobiologia* **342–343**, 241–55.
- R Development Core Team (2006) *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. Available from URL: <http://www.R-project.org>. Accessed on 5 May 2006.
- Raffaelli D. (1999) Nutrient enrichment and trophic organisation in an estuarine food web. *Acta Oecologica* **20**, 449–61.
- Rönkä M. T. H., Saari C. L. V., Lehtikainen E. A., Suomela J. & Häkkinen K. (2005) Environmental changes and population trends of breeding waterfowl in northern Baltic Sea. *Ann. Zool. Fenn.* **42**, 587–602.
- Taft O. & Haig S. (2006) Importance of wetland landscape structure to shorebirds wintering in an agricultural valley. *Land. Ecol.* **21**, 169–84.
- Taylor R., Fletcher R. L. & Raven J. A. (2001) Preliminary studies on the growth of selected 'green tide' algae in laboratory culture: effects of irradiance, temperature, salinity and nutrients on growth rate. *Bot. Mar.* **44**, 327–36.
- Traut A. H. & Hostetler M. E. (2004) Urban lakes and waterbirds: Effects of shoreline development on avian distribution. *Landsc. Urban Plan.* **69**, 69–85.
- Van Eerden M. R., Piersma T. & Lindeboom R. (2003) Competitive food exploitation of smelt *Osmerus eperlanus* by great crested grebes *Podiceps cristatus* and perch *Perca fluviatilis* at Lake IJsselmeer, The Netherlands. *Oecologia* **93**, 463–74.
- Van Eerden M. R., Drent R. H., Stahl J. & Bakker J. P. (2005) Connecting seas: Western Palearctic continental flyway for water birds in the perspective of changing land use and climate. *Global Change Biol.* **11**, 894–908.
- Van Impe J. (1985) Estuarine pollution as a probable cause of increase of estuarine birds. *Mar. Pollut. Bull.* **16**, 271–6.
- Vasas V., Lancelot C., Rousseau V. & Jordán F. (2007) Eutrophication and overfishing in temperate nearshore pelagic food webs: a network perspective. *Mar. Ecol. Prog. Ser.* **336**, 1–14.
- Velasco J., Lloret J., Millán A. *et al.* (2006) Nutrient and particulate inputs into the Mar Menor lagoon (SE Spain) from an intensive agricultural watershed. *Water, Air, Soil Pollut* **176**, 37–56.
- Venables W. N. & Ripley B. D. (2002) *Modern Applied Statistics with S*, 4th edn. Springer Verlag, New York.
- Verdiell D., Andreu A., Egea A., Oliva-Paterna F. J. & Torralva M. (2007) Dinámica espacio-temporal de la familia *Mugilidae* en las áreas someras del Mar. Menor (SE, Murcia): Estados alevines y juveniles. In: *Actas III Congreso de la Naturaleza de la Región de Murcia* (ed. V. Hernández) pp. 117–23. Asociación de Naturalistas del Sureste (ANSE), Murcia, Spain.
- Wetlands International (2006) *Waterbird Population Estimates*, 4th edn. Wetlands International, Wageningen, The Netherlands.