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Exploring NAO influence on waterbirds abundance through hydrological changes in a Mediterranean coastal wetland.

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ABSTRACT

Exploring NAO influence on waterbirds abundance through hydrological changes in a Mediterranean coastal wetland.

Predicting how waterbird populations may respond to climate change is a major challenge for conservation, which could be addressed by understanding the effects of large-scale climate oscillations, such as the North Atlantic Oscillation (NAO), on breeding population size. Here, we explore the relationship between the NAO position and the abundance of waterbird breeding pairs in a protected Mediterranean coastal wetland (Mouth of the Guadalhorce River, Málaga, southern Iberian Peninsula). We found a significant and negative relationship between the winter NAO index and the abundance of grebes ($r=-0.72$, $N=15$, $p<0.01$), rails ($r=-0.74$, $N=15$, $p<0.01$), diving ducks ($r=-0.56$, $N=15$, $p<0.05$) and dabbling ducks ($r=-0.54$, $N=15$, $p<0.05$). Our results suggest that this relation is mediated by the NAO indirect effects on wetland flooded surface via changes in winter precipitation and Mediterranean sea level. These results should be considered to design appropriate environmental management strategies devoted to preventing or mitigating potential deleterious effects of the NAO variability on Mediterranean wetlands ecosystems and preserving their valuable waterbird communities.

KEYWORDS: Guadalhorce River mouth, flooded surface, rainfall, local sea level, waterfowl, winter NAO index

RESUMEN

Exploración de la influencia de NAO en la abundancia de aves acuáticas a través de cambios hidrológicos en un humedal costero mediterráneo

Predecir cómo responden las poblaciones de aves acuáticas al cambio climático es un reto importante para la conservación, que puede abordarse comprendiendo los efectos de las oscilaciones climáticas a gran escala, como la Oscilación del Atlántico Norte (NAO), sobre el tamaño de las poblaciones reproductoras. En este trabajo exploramos la relación entre la posición de la NAO y la abundancia de parejas reproductoras de aves acuáticas en un humedal costero mediterráneo protegido (desembocadura del Río Guadalhorce, Málaga, Sur de la península Ibérica). Encontramos una relación significativa y negativa entre el índice de la NAO y la abundancia de zampullines ($r=-0.72$, $N=15$, $p<0.01$), rálidos ($r=-0.74$, $N=15$, $p<0.01$), patos buceadores ($r=-0.56$, $N=15$, $p<0.05$) y patos nadadores ($r=-0.54$, $N=15$, $p<0.05$). Nuestros resultados sugieren que esta relación está mediada por los efectos indirectos de la NAO sobre la superficie inundada del humedal, a través de cambios en las precipitaciones invernales y en el nivel del mar. Estos resultados pueden ser de utilidad en el diseño de estrategias de gestión ambiental enfocadas a prevenir o mitigar los potencia-

les efectos negativos de la variabilidad de la NAO sobre las comunidades de aves acuáticas en humedales mediterráneos.

PALABRAS CLAVES: Desembocadura del Guadalhorce, superficie inundada, precipitación, nivel del mar local, aves acuáticas, índice NAO invernal.

INTRODUCTION

Climate has a profound influence on biological systems at different scales, from organisms to ecosystem dynamics (Straile et al., 2003; Hallet et al., 2004; Harris et al., 2018), affecting -among others- the abundance, behaviour, and spatiotemporal distribution of populations (Wen et al., 2011; Carvalho et al., 2013; Moreno-Ostos et al., 2012, 2014; Pavón-Jordán et al., 2019). In the present context of global climate change, it is worthy to achieve a better understanding of how species, populations and communities are influenced by climate (Muñoz et al., 2013). However, finding climate and meteorology forcing variables that effectively control the ecological processes is often a challenge (Gordo et al., 2011).

Large-scale climatic oscillators, such as the North Atlantic Oscillation (NAO), are related to significant changes in local weather conditions that, in turn, drive the dynamics of the ecosystems (Trigo et al., 2004; Vicente-Serrano & Cuadrat, 2007). The NAO is frequently characterized through the NAO index (Wallace & Gutzler, 1981; Hurrell & Van Loon, 1997), which is defined as the fluctuation of sea level pressure between the Atlantic subpolar low-pressure zone, located around Iceland, and the Atlantic subtropical high-pressure zone, located around the Azores (Hurrell, 1995). Positive phases of the NAO index occur when the pressure difference between the subpolar and subtropical regions is high. By contrast, negative phases of the NAO index occur when the smaller pressure difference between both regions happens. Variations between the NAO phases have a marked impact on European weather (Trigo et al., 2002; Bojariu & Giorgi, 2005; Tsanis & Tapoglou, 2019), and their effects vary regionally (Hurrell, 1995). Thus, it is well-known that positive values of the NAO index are associated with warmer and wetter conditions in northern Europe, while colder and drier conditions are observed during negative phases of the NAO index. The opposite pattern occurs in southern Europe (Visbeck et al., 2001; Bojariu & Giorgi, 2005; Tsanis & Tapoglou, 2019). In the Mediterranean region, the positive NAO is related to low precipitation and droughts (Trigo et al., 2004; Vicente-Serrano & Cuadrat, 2007; Brandimarte et al., 2011; Bladé et al., 2012; Montaldo & Sarigu, 2017), while in northern Europe prevails wetter conditions (Hurrell et al., 2003). In this context, Quadrelli et al. (2001) showed that the position of the NAO explains most of the interannual rainfall variability in the Mediterranean region.

Consequently, the NAO can influence ecological processes through changes in local weather conditions (Hallet et al., 2004). It has been demonstrated that shifts between the NAO phases induce effects on the distribution, abundance, and reproduction of many vegetal and animal species, both terrestrial (OrlandiW et al., 2010; Salvidio et al., 2016) and aquatic (Melero-Jiménez et al., 2017; Muñoz-Expósito et al., 2017). In this context, bird communities are especially susceptible to changes in the NAO position due to the high dependence of many of their relevant biological processes, such as migration and breeding, on local weather conditions (Burger, 1974; Faaborg, 1976; Nudds, 1982; Moss & Moss, 1993; Battisti et al., 2006; Saunders et al.,2021). In the Mediterranean region, the effects of the NAO on bird populations dynamics have been studied in a wide variety of groups, including seabirds (Jenouvrier et al., 2009), waterbirds (Almaraz & Amat, 2004; Figuerola, 2007; Bechet & Johnson, 2008), raptors (Costantini et al., 2010) and songbirds (Grosbois et al., 2006).

Waterbird populations are especially vulnerable to climate change because their habitats are highly exposed to fluctuating climatic conditions

(Sofaer et al., 2016). This is particularly noticeable in Mediterranean wetlands, considered as biodiversity hotspots (Perennou et al., 2020). The present field research aims to explore the main links between NAO, local-scale meteorological and hydrological conditions, and breeding waterbirds in a protected and strongly anthropized Mediterranean coastal wetland, the Guadalhorce River mouth (Málaga). We also discuss the relationships between this climatic oscillation and the different waterbirds groups, with the aim that our findings could help to promote conservation actions in this artificial wetland and other similar ecosystems in the current context of environmental changes. Following Peters (1991), our observational field results are valuable for designing future experiments and numerical modelling to confirm unambiguously causal relationships.

MATERIAL AND METHODS

Study area

The mouth of the Guadalhorce River (36º 40' 23.3'' N, 4º 27' 20.8'' W) is a coastal wetland hydrologically confined between two branches of the Guadalhorce River and the Mediterranean Sea (Fig. 1). After years of sand quarrying and gravel extraction during the decades of the seventies and the eighties of the last century, several ponds were originated in the area and provided an ideal habitat for waterbirds. In 1989, this area was legally protected by the Government of Andalusia. At the beginning of the present century, the wetland underwent intense hydrological and ecological rehabilitations and currently, it comprises eight permanent shallow ponds (Moreira et al., 2005; Montes-Pérez et al., 2020a; Montes-Pérez et al., 2020b). Annual water level variations in these lagoons reach 50-60 cm and are mainly dependent on groundwater level and, to a lesser extent, rainfall. Groundwater levels are influenced by the Mediterranean Sea through changes in sea level and tides, which have an effect on aquifer piezometric levels and hence on wetland surface. All the small lagoons in the wetland are permanent because they receive water from the aquifer, both in dry and wet years (Nieto et al. 2016, 2020). The main water output from this wetland is evaporation (Montes-Pérez et al., 2020b).

Conductivity in the lagoons varies according to the distance to the coastline and seasonally, ranging between 15.76 mS/cm in the upstream

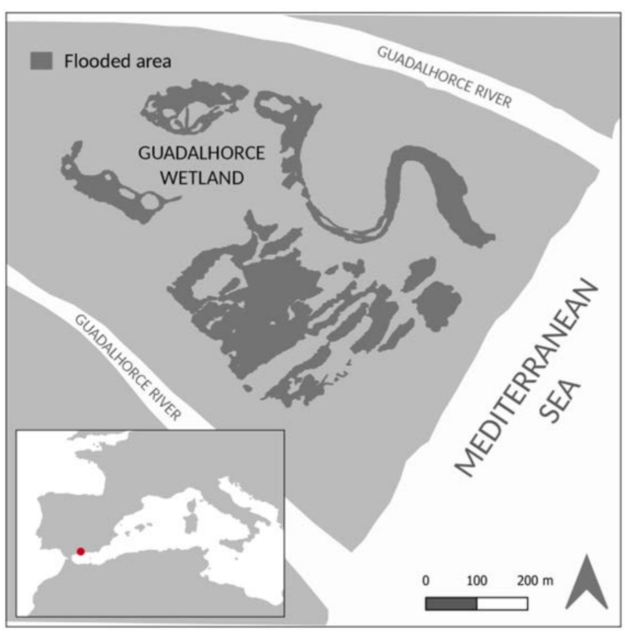

Figure 1. Location of Guadalhorce River mouth coastal wetland in the Iberian Peninsula (Málaga, southern Spain). *Localización del humedal costero de la desembocadura del río Guadalhorce en la Península Ibérica (Málaga, Sur de España).*

lagoon in winter and 85.49 mS/cm measured in those lagoons closest to the seashore in summer (Nieto-López et al., 2020). Attending to trophic status, the lagoons in the wetland have been classified as eutrophic (Montes-Pérez et al., 2020), as they are exposed to several anthropic pressures, such as intensive agriculture, a nearby wastewater treatment plant, and a large urban area (Moreira et al., 2005).

Despite intense anthropic pressures, this ecosystem constitutes an internationally recognised site for waterbirds (Alba & Garrido, 1986) and is listed as an Important Bird Area (IBA ES224) (Mateo-Ramírez et al., 2021). Populations of globally endangered species, such as the White-headed Duck *Oxyura leucocephala* and Kentish Plover *Charadrius alexandrinus*, overwinter and breed in their lagoons. The Andalusian Government protected this wetland to preserve its biodiversity and high environmental value (Nieto-López et al., 2020).

In this study, the mouth of the Guadalhorce River wetland has been considered as a unit, in a large spatial scale integrative approach that does not pretend to make a more detailed (or fine-grained) analysis considering the hydrological particularities of each one of the small lagoons that compose it.

The NAO index data

The winter NAO index data was applied since most of the interannual variability of the NAO position is observed during boreal winter (Hurrell, 1995). We included an 18-year dataset (from 2002 to 2019) of the winter NAO index data obtained from the Climate Data Guide of the National Centre for Atmospheric Research (NCAR) at http://climatedataguide.ucar.edu/climate-dta/hurrell-north-atlantic-oscillation-nao-index-station-based. This winter NAO index is based on the difference of normalized sea level pressure (SLP) between Lisbon (Portugal) and Stykkisholmur/Reykjavik (Iceland) recorded since 1864. The SLP values at each station were normalized by removing the long-term mean and by dividing the long-term standard deviation. Both the long-term means and standard deviations are based on the 1864-1983 period. Normalization is used to avoid the series being dominated by the greater variability of the northern station (Hurrell, 1995; Hurrell et al., 2003; Hurrell & Deser, 2010).

Local meteorological and hydrological variables

To analyse the impact of the NAO on local weather conditions we have studied an 18-year (from 2002 to 2019) daily rainfall data recorded by a meteorological station of the *Instituto de Investigación y Formación Agraria y Pesquera* (IFAPA, Andalusian Government) located nearby the studied wetland. Winter accumulated rainfall (December to February) was also calculated for each studied year as the NAO is known to influence South European weather especially through changes in winter rainfall (Quadrelli *et al*., 2001).

Wetland flooded surface was estimated using QGIS based on a set of 10 aerial photographs available on Google Earth© corresponding to the start of the breeding season (March to May) from 2005 to 2016. Flooded surfaces corresponding to 2004, 2006, 2008, 2017 and 2018 were excluded because of photographs lacking.

The average sea level in Málaga at the beginning of the breeding season was used as a proxy of Mediterranean Sea influence on the Guadalhorce wetland hydrological features. Data from Málaga tide-gauge was obtained from Puertos del Estado (Ministerio de Transportes, Movilidad y Agenda Urbana, Spanish Government) at https://www.puertos.es/es-es/oceanografia/Paginas/portus.aspx.

Censuses of waterbird breeding pairs

Waterbird abundances were obtained from the database of the monitoring program of breeding waterbirds in Andalucía, promoted by Agencia de Medio Ambiente y Agua (Junta de Andalucía) in 2004. For these censuses, and over a 15-year period (from 2004 to 2018), the number of breeding pairs of each species was obtained from direct observation, using binoculars and spotting scopes at selected sites along the wetland edges. All surveys were conducted in a standardised manner throughout the study period. Given that all of the waterbirds included in this study were large and

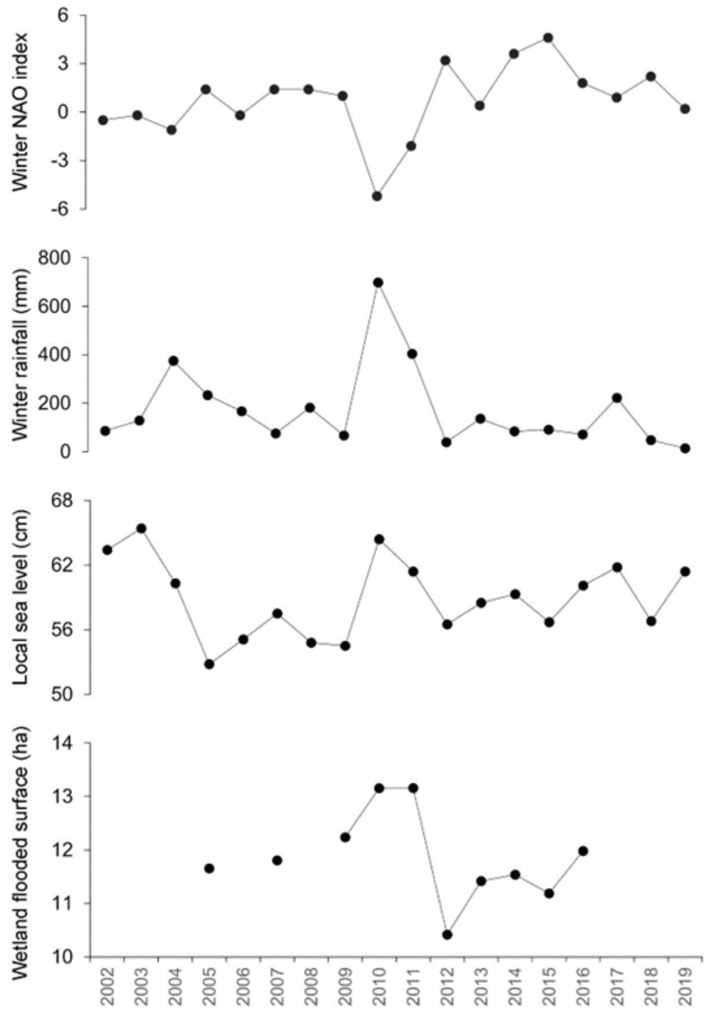

Figure 2. Annual changes in the winter NAO index, winter accumulated rainfall, local sea level and wetland flooded surface. *Cambios anuales en el índice NAO invernal, en la precipitación acumulada durante el invierno, en el nivel del mar en Málaga y en la superficie inundada del humedal.*

easily detectable, and that every count was carried out by the specialised staff of the Andalusian environmental institution, we assume that there are few detection errors and that the direct counts showed a high accuracy level (Bibby et al., 2000, Moreno-Ostos et al., 2014).

Waterbird species were classified into four groups: diving ducks (White-headed Duck *Oxyura leucocephala* and Common Pochard *Aythya ferina*), dabbling ducks (Mallard *Anas platyrhynchos* and Gadwall *Mareca strepera*), grebes (Little Grebe *Tachybaptus ruficollis*) and rails (Common Moorhen *Gallinula chloropus* and Eurasian Coot *Fulica atra*).

Statistical analysis

The length of the data series on the winter NAO index, meteorology, wetland flooded surface, local sea level, and waterfowl breeding pairs cen-

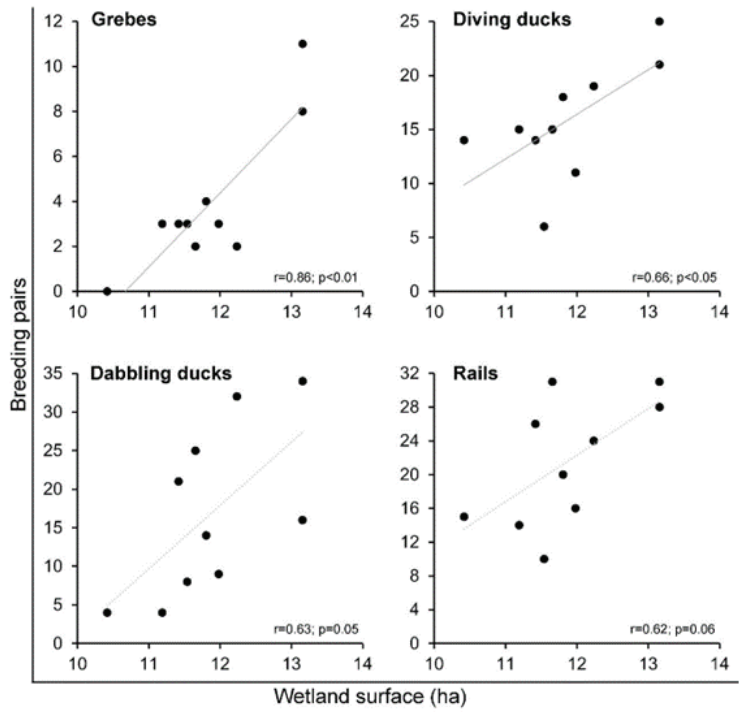

Figure 3. Relationship between the wetland flooded surface and the number of waterbirds breeding pairs for the different groups considered. *Relación entre la superficie inundada del humedal y el número de parejas reproductoras de aves acuáticas de los diferentes grupos considerados.*

suses depended on their availability from the various sources and providing institutions.

Pearson's correlation analysis was used to describe the relationships between waterfowl censuses and environmental variables.

In addition, we conducted a path analysis (Sokal & Rholf, 1995) to explore the strength and sign of direct and indirect effects of the NAO and related meteorological (i.e., rainfall) and hydrological (i.e., sea level, wetland flooded surface) variables on the studied waterbirds groups breeding pairs.

RESULTS

The North Atlantic Oscillation is correlated to winter rainfall, local sea level, and wetland inundation surface

During the whole study period (2002-2019) the winter North Atlantic Oscillation index ranged between -5.2 in 2010 and 4.6 in 2015 (Fig. 2). Annual changes in the winter NAO index were negatively and significantly correlated to the winter accumulated rainfall recorded in the near vicinity of the wetland (r=-0.80, N=18, $p<0.01$), and to the average spring sea level in Málaga (r=-0.54, N=18, $p<0.05$; Fig. 2), showing that low values of the winter NAO index were coupled to high local rainfall values and sea level rise, while winter rainfall and sea level declined during the positive NAO phases.

The wetland flooded area during spring also showed interannual variability, ranging from 10.4 ha in 2012 to 13.1 ha in 2010 and 2011, with a mean value of 11.85 ha. Wetland surface in spring was positively correlated to winter accumulated rainfall (r=0.76, N=10, $p<0.01$; Fig. 2) and local sea level (r=0.59; N=10; $p<0.05$; Fig. 2). In addition, the winter NAO index was negatively correlated to the wetland flooded surface (r=-0.84; N=10; $p<0.01$; Fig. 2).

Implications for waterbird breeding pairs

The wetland flooded area at the beginning of the

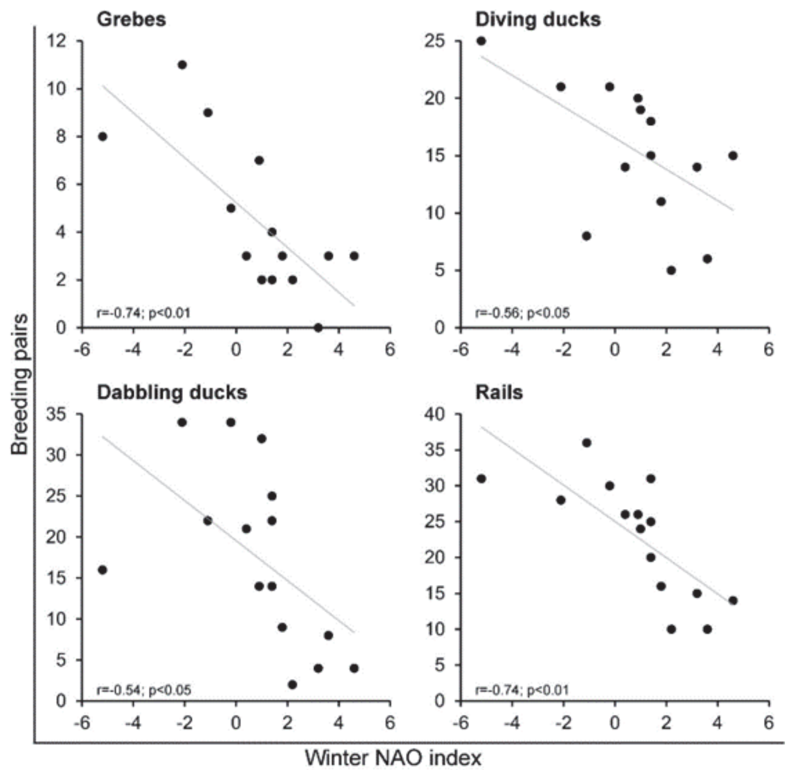

Figure 4. Relationship between the winter NAO index and the number of waterbirds breeding pairs for the different considered groups. *Relación entre el índice NAO invernal y el número de parejas reproductoras de aves acuáticas de los diferentes grupos considerados.*

breeding season was significantly correlated to the abundance of grebes (r=0.86, N=10, p<0.01) and diving ducks (r=0.66, N=10, p<0.05) breeding pairs (Fig. 3). However, this relation was marginally significant for dabbling ducks (r=0.63, N=10, p=0.05) and rails (r=0.62, N=10, p=0.06) breeding pairs.

As a general trend, the abundance of breeding waterbirds in the wetland increased during the negative NAO phases and decreased when the positive NAO phases occurred (Fig. 4, Table 1). This inverse relationship was stronger in the case of grebes (r=-0.74, N=15, p<0.01) and rails (r=-0.74, N=15, p<0.01), especially to Eurasian Coot (Table 1), and slightly weaker for dabbling ducks (r=-0.54, N=15, p<0.05) and diving ducks (r=-0.56, N=15, p<0.05). However, this relationship was not statistically significant for Mallards, Common Moorhen and Common Pochard (Table 1).

Path analysis (Table 2) allowed us to explore the direct or indirect nature of these relationships. In the Guadalhorce wetland, we found a direct negative effect of the winter NAO index on dabbling ducks, diving ducks, and rails. By contrast, wetland flooded surface depicted a positive direct effect on dabbling ducks, diving ducks, and grebes, and sea level also had a positive direct

Table 1. Correlation coefficient and significance level of the relationship between the winter NAO index and the number of breeding pairs for each waterbird species. *Coeficiente de correlación y nivel de significancia de la relación entre el índice NAO invernal y el número de parejas reproductoras de cada especie de aves acuáticas.*

Group	**Waterbird species**	**winter NAO index**	
		r	***p***
Dabbling ducks	*Anas platyrhynchos*	-0.43	0.1
	Mareca strepera	-0.59	<0.05
Rails	*Fulica atra*	-0.71	<0.01
	Gallinula chloropus	-0.39	0.15
Diving ducks	*Oxyura leucocephala*	-0.54	<0.05
	Aythya ferina	-0.4	0.13
Grebes	*Tachybraptus ruficollis*	-0.72	<0.01

effect in the case of grebes.

Attending to the indirect effects, the NAO winter index exerted a negative indirect effect on all the studied waterbird groups (except for rails) via wetland inundated surface. In addition, rainfall and sea level positively influenced the abundance of dabbling and diving ducks via the wetland flooded surface.

Indirect pathway coefficients were always higher for the influence of precipitation on waterbirds abundance than in the case of sea level variations, suggesting a more relevant role of this meteorological variable as a driver of the wetland flooded surface and waterfowl numbers.

DISCUSSION

The North Atlantic Oscillation significantly correlated with the abundance of different breeding waterbird species in the protected Guadalhorce River mouth wetland. The abundance of waterbirds declined during positive phases of the NAO and increased during low values of the NAO index. Changes in rainfall and local sea level and the associated changes in the wetland flooded surface were the local meteorological and hydrological intermediaries in this relationship in the case of grebes and diving ducks. In addition, rainfall had a delayed effect as demonstrated in other ecosystem processes (Gouveia et al., 2008), since winter rainfalls influence the wetland flooded area during spring. This suggests that rainfall may exert part of its influence on the flooded surface through the recharge of the aquifer that feeds the wetland.

Previous studies have highlighted the importance of wetland characteristics in the selection of waterbird breeding sites such as flooded area, water depth, or vegetation cover (Burger, 1974; Faaborg, 1976; Nudds, 1982; Moss & Moss, 1993; Battisti *et al*., 2006; Meniaia et al., 2014) which are mostly driven by rainfall, among other variables. However, as our results suggest, the intensity of the relationship between climatic, meteorological, and hydrological variables and the number of breeding pairs depends on the waterbird group.

Grebes show a strong Pearson's correlation with the NAO position, but path analysis revealed that this relation is mainly mediated by the direct effects of wetland flooded surface and sea level variations. Changes in the flooded surface could be connected to wetland depth variations (Carvalho et al., 2013), which are strongly linked to the reproductive success of Little Grebe (Moss & Moss, 1993). This species feeds

Table 2. Main direct and indirect effects of the NAO winter index, accumulated rainfall, wetland flooded surface, and local sea level on the studied waterbirds breeding pairs. The sign and value of the direct and indirect path coefficients are shown between brackets. BP means breeding pairs. *Principales efectos directos e indirectos del índice NAO invernal, la precipitación acumulada, la superficie inundada del humedal y el nivel medio del mar en Málaga sobre el número de parejas reproductoras de los grupos de aves acuáticas estudiados. Entre paréntesis se muestra el signo y valor de los coeficientes de efectos directos e indirectos. BP significa parejas reproductoras.*

Group	Direct effects	Indirect effects
Dabbling ducks	NAO → BP (-3.22)	NAO → wetland surface → BP (-8.32)
		Rainfall → wetland surface → BP (7.53)
	Wetland surface → BP (0.05)	Sea level → wetland surface → BP (5.85)
Diving ducks	NAO → BP (-0.81)	NAO → wetland surface → BP (-0.04)
		Rainfall → wetland surface → BP (0.04)
	Rainfall → BP (0.19)	Sea level → wetland surface → BP (0.03)
Grebes	Wetland surface → BP (2.70)	NAO → wetland surface → BP (-2.27)
	Sea level → BP (0.28)	NAO → sea level → BP (-0.18)
Rails	NAO → BP (-2.91)	No indirect effects found

on benthic invertebrates (insects, molluscs, crustaceans), amphibians, and small fishes that they capture mainly by diving (Cramp & Simmons, 1977; Ceccobelli & Battisti, 2010), which requires enough water availability (Athamnia et al., 2015). Diving ducks depict a similar response to changes in the NAO, also showing a significant Pearson's correlation with wetland flooded surface and with the NAO position, although weaker than in the case of grebes. Again, indirect effects of the NAO in the rain, sea level and wetland surface are at the base of this relationship. In this context, previous studies suggest that inundation area appears to be a relevant factor during nest-site selection for White-headed Ducks (Almaraz & Amat, 2004; Nergiz et al., 2011; Atiénzar et al., 2012) and Common Pochard (Folliot et al., 2017; Broyer & Bourguemestre, 2020). White-headed Duck selects large ponds with open water and deep areas to breed (Armengol et al., 2008; Sebastián-González et al., 2013).

In the case of rails and dabbling ducks, Pearson's correlation between wetland flooded surface and the abundance of breeding pairs were not significant. This relation seems to exist although it is not strong enough to reach the established level of statistical significance. In addition, a significant relationship between the NAO position and the number of breeding pairs was found. In agreement, path analysis revealed a strong negative direct effect of the NAO both in dabbling ducks and rails. In the case of dabbling ducks this relationship seems to be a consequence of the indirect effects of rain and, to a lesser extent, sea level variations on the wetland flooded surface. In the case of rails, although we found a strong negative direct effect of the NAO on rails breeding pairs, path analysis couldn´t find the indirect causes of this relationship. Maybe it is mediated by other variables not considered in this study, such as vegetation density, which could constitute a force driving nest-site selection for these waterbird groups (Battisti et al., 2006; Samraoui & Samraoui, 2007; Causarano & Battisti, 2009; Meniaia et al., 2014; Athamnia et al., 2015; Fouzari et al., 2018). Wetland vegetation, which is closely linked to water availability, protects from predators (Martin, 1995; Angelici et al., 2012) and could enhance reproductive success (Thomas et al., 1999; Samraoui & Samraoui, 2007; Meniaia et al., 2014).

The effects of the NAO on waterbird dynamics have been previously studied in the Mediterranean region. Almaraz & Amat (2004) showed that the NAO index is related to the population dynamics of the endangered White-headed Duck in the southwestern Mediterranean region. They demonstrated that low values of the winter NAO index were associated with increased rainfall, which favoured the expansion of the species range during the following breeding season, as a result of an increase in the wetlands area in Spain. A greater extension of wetlands increases habitat size, food availability and, therefore, opportunities for reproduction. Similarly, Figuerola (2007) found that the number of Black-winged Stilt *Himantopus himantopus* breeding pairs was negatively related with the NAO index in the Doñana National Park wetlands (southwestern Spain). Consistently, the NAO position influenced the extent of Doñana marshlands and, consequently, the philopatry and dispersal behaviour of this species (Figuerola, 2007).

The influence of the NAO on waterbirds has also been detected in populations that use highly anthropized habitats for reproduction, as Bechet & Johnson (2008) showed in the case of the Greater Flamingo *Phoenicopterus roseus* in the salt marshes of the Camargue (Southern France). They found that the NAO was negatively correlated with local hydrological conditions, so low winter NAO values were related to high water levels in the main lagoon of the Camargue, the Vaccares lagoon, and this favoured an increase in the number of Greater Flamingo breeding pairs.

Understanding how waterbirds are influenced by global climate oscillations and the related local meteorological and hydrological variables is necessary to anticipate the consequences of climatic variations on these species' dynamics and will be of particular interest in the case of critically endangered species, such as the White-headed Duck. Previous studies have provided NAO-modelled scenarios over the upcoming decades taking into account the role of the increase of Greenhouse Gases (GHG) concentration in the atmosphere and most of them concluded that positive NAO phases will become more frequent throughout the

21st century (Ulbrich & Christoph, 1999; Gillet *et al*., 2002; Gillet *et al*., 2003; Osborn, 2004; Stephenson *et al*., 2006; Tsanis & Tapoglou, 2019).

Regarding the local meteorology, the expected future trends for the NAO will have effects on the temperature and precipitation patterns of Europe (Bojariu & Giorgi, 2005; Stephenson *et al*., 2006; Deser et al., 2012, 2017; Tsanis & Tapoglou, 2019). Stephenson *et al*. (2006) analysed eighteen models and all of them showed a similar increasing NAO-like pattern in temperature and precipitation trends with increasing amounts of carbon dioxide: strong warming over most of Europe and increasing/decreasing precipitation in northern/southern Europe, respectively. Deser *et al*. (2017) estimated a >85% chance of decreasing winter precipitation over north-western Africa and regions directly adjacent to the Mediterranean Sea for the next 50 years, consistent with the argument Tsanis & Tapoglou (2019) suggested an increase in drought events in Spain as the number of years with positive NAO is predicted to increase in the next 80 years. Following these modelled scenarios for the future NAO variability in the context of present global changes, it is expected that drought conditions will prevail in Mediterranean wetlands. The NAO also exerts a significant control on the Mediterranean Sea level (Tsimplis et al., 2013; Martínez-Asensio et al. 2014). In the specific case of the Guadalhorce wetland, the expected NAO increasing trends may contribute to a decrease in local sea level and its influence on the aquifer and, as a consequence, on the flooded wetland surface, the key determinant of waterbird abundance.

Gibbs (1993) demonstrated that small wetlands play an important role in the dynamics of metapopulations of certain species, as may be the case of some endangered ducks with a regular presence in our study area (e.g., the Ferrugineous Duck *Aythya nyroca*, the Marble Duck *Marmaronetta angustirostris*, and the already cited White-headed Duck *Oxyura leucocephala*). Therefore, the value for the conservation of the Guadalhorce River mouth wetland is expected to increase in the near future since it is a small, protected area where adequate management measures are feasible, including hydrological management (i.e., artificial flooded area regulation, controlled depth of the lagoons, small islands creation, among others). Given its strategic geographical location, and the characteristics of the studied species, we highlight the importance of enforcing long-term monitoring, especially focused on threatened species, as well as fostering international linkages and conservation programs with wetlands of north-western Africa to preserve these key habitats and favour metapopulation dynamics.

Although the existence of significant correlation does not necessarily imply causation, our results based on field observations are valuable for the design of future experiments and numerical models with the capacity to unequivocally confirm the causal relationships linking NAO, local meteorological and hydrological conditions, and breeding waterbirds numbers in this complex protected wetland.

In conclusion, the abundance of breeding waterbirds in this Mediterranean coastal wetland seems to be conditioned by the NAO variability. In particular, negative phases of the NAO are related to an increase in waterbird breeding pairs, whereas the contrary occurred under a positive NAO index. In the case of grebes and diving ducks, this relation is mediated by the NAO indirect effects on the wetland inundation surface via changes in water precipitation and Mediterranean Sea level . For rails and dabbling ducks, this relation could also be mediated by the same meteorological and hydrological variables, although available data in this paper was not enough to show statistical significance. In addition, for these groups the relation could also be mediated by other variables not considered in this study (e.g., riparian vegetation density). Our results should be considered to design appropriate environmental management strategies devoted to preventing or mitigating potential deleterious effects of the NAO variability on Mediterranean wetlands ecosystems and to preserve its valuable associated waterbird communities.

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