Diet of great cormorants *Phalacrocorax carbo* in the Sado estuary, Portugal, and possible impacts on local fisheries and aquaculture

Dieta do Corvo-marinho (*Phalacrocorax carbo*) no estuário do Sado, e possíveis impactos na pesca e na aquacultura

Paulo Catry[1*], Ana Campos[2], Teresa Catry[3], Carlos Assis[4], Susana Pereira[5], José Pedro Granadeiro[3]

ABSTRACT

Great cormorants are important predators in freshwater, brackish and coastal marine habitats, often with a significant impact on fish communities and ecosystem functioning. Great cormorants have shown a marked increase in Europe, and knowledge on their diet and fish consumption are important, especially because cormorants are at the origin of conflicts between fishermen and fish-farmers, and wildlife. In the Sado estuary cormorants feed mostly on mullets (Mugilidae), toadfishes *Halobatrachus didactylus* and seabreams (Sparidae), but they also prey on a large diversity of other species. We have evidence that the analysis of diet based on otoliths underestimates the occurrence of small pelagic fish, such as anchovies *Engraulis encrasicolus* and sand-smelts *Atherina presbyter*, which, together with various flatfishes, have been recorded as important prey in other Portuguese wetlands. Important species for local fisheries and aquaculture were of little importance in cormorant diet. A comparison between the estimated consumption by cormorants and the estuarine stocks and fish-farm production leads to the tentative conclusion that the overall economic impact of these birds is small. However, it is important to keep in mind that this does not mean that cormorants are unimportant predators at individual fish-farms; in fact, it is plausible that cormorants may have a significant impact for some individual producers that are unable to effectively deter the birds from feeding on particular ponds.

Keywords: human-bird conflicts, Great cormorant, diet, fisheries, fish farms, foraging ecology

1* MARE – Marine and Environmental Sciences Centre, ISPA - Instituto Universitário, Rua Jardim do Tabaco 34, 1149-041 Lisboa, Portugal **2** Rua Arco do Carvalhão 25, 2° dto. 1070-008 Lisboa. **3** CESAM - Centro de Estudos do Ambiente e do Mar, Departamento de Biologia Animal, Faculdade de Ciências da Universidade de Lisboa, 1749-016 Lisboa, Portugal. **4** MARE – Marine and Environmental Sciences Centre, Departamento de Biologia Animal, Faculdade de Ciências da Universidade de Lisboa, 1749-016 Lisboa, Portugal. **5** Av. Brasil, 90, 2° Dto. 1700 073 Lisboa

*** Corresponding author:** paulo.catry@gmail.com

RESUMO

Os corvos-marinhos são predadores importantes em habitats dulçaquícolas, estuarinos e marinhos costeiros, frequentemente tendo um impacto significativo sobre as comunidades de peixes e o funcionamento dos ecossistemas. As populações destas aves registaram um incremento marcado na Europa, e o conhecimento sobre a sua dieta e consumo de peixe é importante, tanto mais que os corvos-marinhos estão na origem de conflitos importantes entre pescadores, aquicultores e a vida selvagem. No estuário do Sado, os corvos marinhos alimentam-se sobretudo de tainhas (Mugilidae), charrocos *Halobatrachus didactylus* e alcorrazes e sarguetas (Sparidae), consumindo também uma grande diversidade de outras espécies. Temos indicações, contudo, de que a caracterização da dieta com base em otólitos subestimou a ocorrência de pequenos peixes pelágicos, tais como o biqueirão E*ngraulis encrasicolus* e o peixe-rei *Atherina presbyter* que, tal como vários Pleuronectiformes, foram registados como presas importantes noutras zonas húmidas portuguesas. Espécies importantes nas pescas e na aquacultura no estuário do Sado foram elementos comparativamente pouco importantes da dieta. Comparando o consumo estimado dos corvos-marinhos com os stocks de peixe no estuário e com a produção piscícola nas aquaculturas, parece poder-se concluir que o impacto económico global das aves é reduzido. Contudo, é importante ter-se em conta que esta conclusão não invalida que os corvos-marinhos possam ter impactos significativos em certos tanques de produção piscícola. Na verdade, é plausível que as aves tenham um impacto relevante para certos produtores que não conseguiram (ou não puderam) com eficácia desencorajar as aves de se alimentarem em certas aquaculturas.

Palavras-chave: conflitos, Corvo-marinho, dieta, pesca, aquacultura, ecologia alimentar

Introduction

Great cormorants *Phalacrocorax carbo* (hereafter "cormorants") are large bodied, abundant and efficient underwater predators, potentially able to have an impact on fish communities and therefore on the ecology of aquatic ecosystems where they occur in large numbers (Boyd et al. 2006, Karpouzi et al. 2007). The sustained increase of cormorants in Europe has given rise to concerns and conflict with fisheries and aquaculture (Bregnballe et al. 1997, Leopold et al. 1998, Stewart et al. 2005, Lilliendahl & Solmundsson 2006). However, the impact of these birds likely varies regionally, and more studies are needed to assess how frequent and prevalent are occurrences where cormorants do indeed pose a real problem to ecosystems and to human activities. Studies of cormorant diet are also interesting as a means to establish baselines and monitor fish communities (Boström et al. 2012, Dias et al. 2012). In Portugal, great cormorants are almost exclusively wintering birds, with a markedly increasing trend over recent decades (Catry et al. 2010). One of the main wintering areas in Portugal is the Sado river estuary, where frequent complaints about the predatory action of cormorants are voiced, particularly by fish farmers. In this study, our objectives were to (1) characterize cormorant diet in the Sado estuary, (2) estimate annual consumption of key-prey and (3) discuss possible inferences in relation to the cormorant-human conflict.

Methods

This study took place in the Sado estuary (38° 26' N, 08° 45' W), in the west coast of Portugal. This is a large estuary covering 210 km^2, mostly composed of shallow waters and extensive mudflats and sandbanks that are exposed at low tide. Salt marshes are also extensive, and the estuary is surrounded by a large area of salt-pans, most of which have been abandoned or converted into fish-farms.

We studied the diet of cormorants by analysing pellets collected at the main roosting site of the estuary (the islet of Ratão) where almost all the birds spend the night. Pellets were collected in February and March 2012 and monthly between October 2012 and February 2013 (Table 1). Each pellet was kept in an individual plastic bag and frozen until further processing. In the lab, pellets were individually placed in water at 40°C with a digestive enzyme (neutrase) during a period of 4 hours, to allow their disintegration, followed by a short (few minutes) bath in ethanol. Prey identification was mostly based on *sagitta* otoliths, although vertebrae, mouth parts, teeth, pharyngeal bones and teeth, *asteriscus* otoliths (particularly useful to identify Cyprinidae) were also used. For the identification we used our own reference collections of hard structures of the Portuguese fish fauna, as well as published information (Prenda & Granado-Lorencio 1992, Prenda et al. 1997, Assis 2000, Tuset et al. 2008). The occasional molluscs and crustaceans found in pellets were assumed to be secondary prey, originating in fish guts.

Using pellets to study cormorant diet is a common and practical procedure (Carss 1997, Barrett et al. 2007), but one that is not free of biases (Zijlstra & Van Eerden 1995, Votier et al. 2003, Alonso et al. 2013), which must be acknowledged and taken into consideration (see Discussion).

We measured the length of otoliths (excluding eroded ones) to infer fish size and mass (using equations published in Assis 2000). When fish prey were not identified to species

Table 1 - Seasonal distribution of diet samples of Great cormorant (*Phalacrocorax carbo*) obtained at the Sado estuary.

Tabela 1 - Distribuição sazonal das amostras de dieta de Corvo-marinho (*Phalacrocrax carbo*) obtidas no estuário do Sado.

DATE	NUMBER OF PELLETS	NUMBER OF INDIVIDUAL PREY
17-02-2012	67	320
24-02-2012	23	78
10-03-2012	34	170
16-10-2012	30	294
14-11-2012	48	235
27-11-2012	50	257
12-12-2012	31	202
08-01-2013	34	159
28-01-2013	30	88
14-02-2013	30	107
25-02-2013	34	143
TOTAL	411	2053

level, we assumed their mass was the same as the mean mass of other fish of the same genera (or similar ones). For a few rare species for which size was not possible to estimate, we arbitrarily assumed a mean mass of 100 g. For each prey type, the total mass ingested was obtained by multiplying the mean estimated mass for the species by the number of individual items of that species. However, for sand-smelt *Atherina presbyter* and European anchovy *Engraulis encrasicolus*, which have very small otoliths subject to rapid erosion, we considered the largest estimated size, rather than the mean size. Note that we believe that these 2 species were strongly underestimated in diet (see Discussion).

We made fortnightly counts of cormorants at the known roosting sites of the estuary from mid-October to mid-March (the main period of occurrence of the species). To estimate the energetic requirement of cormorants wintering in the Sado estuary we used the model developed by Grémillet et al. (2003). We did not have detailed information on some of the parameters used in this model, in which case either we used the values presented in Grémillet et al. (2003), or we used values adapted to the particular circumstances of the Sado estuary, as depicted in Table 2 and with the following rationale:

> Body mass: this species does not store significant fat reserves in winter. Most wintering birds in Portugal are *Phalacrocorax carbo sinensis* (Catry et al. 2010), while values in Grémillet et al. (2003) refer to P. c. carbo, which is larger (Cramp & Simmons 1977).

> Time resting at night: the night duration at Sado at the winter solstice is 871 minutes, and in early October is 733 minutes (e.g. http://aa.usno.navy.mil/data/docs/Dur_OneYear.php). We have seen cormorants at Sado actively fishing at the beginning of the nocturnal period, but often they also start roosting before dark. Taking these into account, we assumed an interval varying between 750 and 850 minutes. Final output of model is not much influenced by variation in these input values (Grémillet et al. 2003).

> Time resting in daytime: this value is calculated as the remaining time after excluding time resting at night, time flying, time wing-spreading and time in water.

> Time flying: considering that virtually all foraging areas in the estuary are located within a 12km radius of the main nocturnal roosting site at Ratão, we assume that on average a cormorant flies at most 30km per day. Knowing that cormorants fly at 53 km/h (Yoda et al. 2012), we have a mean time in flight of 34 min. For a minimum value we duplicated the 5 minutes figure given by Grémillet et al. (2003) for a cormorant population living in a small lake.

> Time wing-spreading: this species wing-spreads in all kinds of environment and we opted to keep the value provided by Grémillet et al. (2003). Final output of model is not much influenced by variation in these input values (Grémillet et al. 2003).

> Time in water: the value given by Grémillet et al. (2003) is for a population foraging on a lake with a low density of fishes. According to those authors, in more favourable areas (such as estuaries and fish ponds) cormorants spend less time in water.

> Assimilation efficiency: we opted to make this value vary a little, particularly considering that species such as toadfishes, with heavy bone structures, may lead to a lower efficiency.

> Average calorific value of fish: from data published by Bandarra et al. (2004) and Ridgway (2010), plus expert advice (Narcisa Bandarra, pers. com.) we considered extreme values of 3.5 and 5.5Kj/g.

> Dive/pause ratio: we used the extreme values presented by Grémillet et al. (2003).

> Average water temperature: we extracted values from the Sines Buoy from the website of Instituto Hidrográfico and considered a narrow interval to account for the possibility that the water temperature may be slightly lower inside the estuary in winter. Final output of model is not much influenced by variation in these input values (Grémillet et al. 2003).

> Average dive depth: the areas most used by cormorants in the Sado estuary have depths of 5 metres of fewer (bathymetric data from Brito 2009).

Table 2 - Values used in the bioenergetics model used for estimation of daily biomass consumption of great cormorants *(Phalacrocorax carbo)* wintering in the Sado estuary.

Tabela 2 - Valores utilizados para parametrizar um modelo bioenergético que permite estimar a quantidade de peixe consumida por dia por corvos-marinhos (*Phalacrocorax carbo)* invernantes no estuário do Sado.

PARAMETER	Value in Grémillet et al. 2003	Plausible value leading to a minimum consumption at Sado	Plausible value leading to a maximum consumption at Sado
Body mass (kg)	3.2	3.0	3.1
Time resting at night (min./day)	958	850	750
Time resting in daytime (min./day)	337	520	516
Time flying (min./day)	5	10	34
Time "wing-spreading" (min./day)	10	10	10
Time in water (min./day)	130	50	130
Assimilation efficiency	77.6	80	70
Average calorific value of fish (Kj/g)	5.33	5.5	3.5
Underwater swim speed (m/sec.)	1.35	1.35	1.35
Dive / pause ratio	3.46	2.88	4.04
Average water temperature (°C)	6	16	14
Average dive depth (m)	5	2	5

We used the extreme values in Table 2 to produce two estimates of daily fish consumption, and took the mean of those values as a final estimate.

Results

We estimate from the bioenergetics model that each wintering cormorant at Sado consumes 853 g of fish per typical day in autumn/winter, which accords well with other studies on this species (Grémillet et al. 2003, Ridgway 2010).

The number of cormorants counted varied between 659 and 4671 individuals, and their overall presence in the Sado estuary during the autumn-winter was 368,640 cormorants-days. Their estimated annual consumption of fish was 314 tonnes.

We collected 411 pellets containing the remains of 2053 prey-items. Mullets (Mugilidae) dominated the diet both numerically and in terms of biomass, followed by breams (Sparidae) and the Lusitanian toadfish *(Halobatrachus didactylus)*, the other groups being less important (Table 3). There were no clear seasonal trends in diet and we do not present seasonal data for the sake of brevity.

Gilt-head seabream *Sparus aurata* and European seabass *Dicentrarchus labrax*, two of the most important species at Sado fish farms, represented only 1.5% of the mass consumed by cormorants. The contribution of soles *Solea solea* and *Solea senegalensis*, two species of great importance for fish producers, is slightly larger, corresponding to 5% of the consumed biomass (Table 4).

Table 3 - Percentage of total prey (number of individuals) and of biomass of fishes consumed by great cormorants *(Phalacrocorax carbo)* in the Sado estuary, as revealed by analysis of 411 pellets and the identification of 2053 prey items.

Tabela 3 - Percentagem do total de presas (número de indivíduos) e de biomassa consumida por corvos-marinhos *(Phalacrocorax carbo)* no estuário do Sado. Dados obtidos da análise de 411 regurgitações e da identificação de 2053 presas individuais.

Species/Genus/group	Numbers (%)	Mass (%)	Dominant species
Engraulidae	**7.2**	**0.2**	
Engraulis encrasicolus (anchovy)	7.2	0.2	
Belonidae	**1.2**	**0.4**	
Belone belone (garfish)	1.2	0.4	
Serranidae	**0.3**	**0.3**	
Serranus cabrilla (comber)	0.3	0.3	
Clupeidae	**<0.1**	**<0.1**	
Sardina pilchardus (sardine)	<0.1	<0.1	
Cyprinidae (barbs. carps. etc)	2.5	2.0	
Merluccidae	**<0.1**	**<0.1**	
Merluccius merluccius (hake)	<0.1	<0.1	
Batrachoididae	**13.7**	**15.1**	
Halobatrachus didactylus (toadfish)	13.7	15.1	
Mugilidae	**37.2**	**62.5**	
Chelon labrosus (mullet)	0.7	0.6	
Liza aurata (mullet)	3.6	6.2	
Liza ramada (mullet)	7.5	12.9	
Liza sp. (mullet)	5.2	8.9	*Liza ramada. L. aurata*
Mugil cephalus (mullet)	<0.1	<0.1	
Mugilidae non ident. (mullet)	20.1	33.8	*Liza ramada. L. aurata*
Atherenidae	**4.1**	**0.2**	
Atherina presbyter (sand smelt)	4.1	0.2	
Moronidae	**0.5**	**0.6**	
Dicentrarchus labrax (seabass)	0.3	0.3	
Dicentrarchus sp (seabass)	0.2	0.3	*Dicentrarchus labrax*
Sparidae	**19.4**	**10.8**	
Boops boops (bogue)	<0.1	<0.1	
Diplodus sargus (white seabream)	0.1	0.1	
Diplodus sp. (Senegal seabream, anular seabream and others)	16.0	8.8	*D. bellottii. D. annularis*
Pagellus acarne (axillary seabream)	<0.1	<0.1	
Sarpa salpa (salema)	<0.1	<0.1	
Sparus aurata (gilt-head seabream)	1.1	0.9	
Sparidae non ident.	2.1	0.9	
Sciaenidae	**<0.1**	**<0.1**	
Argyrosomus regius (meagre)	<0.1	<0.1	
Blennidae	**0.3**	**0.3**	
Parablennius sp. (blenny)	0.3	0.3	
Bothidae/Soleidae	**10.7**	**5.1**	
Solea/Pegusa (soles)	8.7	4.5	*S. senegalensis. S. solea*
Soleidae (other soles)	0.9	0.1	
Bothidae/Soleidae non ident.	1.1	0.5	*Arnoglossus laterna*
Fishes non ident.	**3.0**	**2.4**	

Table 4 - Mean individual mass of the main prey-types (and of economically important prey) and the estimated annual consumption by the non-breeding Great cormorant *(Phalacrocorax carbo)* population using the Sado estuary. For the breams Sparidae we do not present a mean individual mass, as the family includes fishes with very diverse body shapes.

Tabela 4 - Massa média individual dos principais tipos de presas (e de presas de importância económica) e estimativa do consumo anual pela população de corvos-marinhos *(Phalacrocorax carbo)* invernantes no estuário do Sado. Para os Sparidae não se apresenta a massa individual média, já que esta família apresenta formas corporais muito diversas.

SPECIES	MEAN MASS (g)	TOTAL MASS (ton.)
Mullets Mugilidae	212.5	196.5
Toadfish	139.5	47.5
Seabass	130.7	1.9
Sparidae (breams)		34.0
Gilt-head seabream	105.2	2.8
Soles *(Solea/Pegusa)*	66.1	14.2

Discussion

Great cormorants are generalist fish predators (e.g. Cramp & Simmons 1977, Suter 1997, Liordos & Goutner 2008, Boström et al. 2012, Veen et al. 2012), and they mostly took very abundant fishes of the Sado estuary (Lopes da Cunha 1994, Neves et al. 2008), such as various mullets, toadfish and Senegal sea breams, with a variety of other species in smaller numbers. These results are considerably different from those of other studies on the diet of cormorants in other Portuguese coastal wetlands. At Ria Formosa, for example, sand-smelt dominated by numbers, even if mullets and toadfish were also frequent (Grade 1996, Grade & Granadeiro 1997). At the Minho estuary, flatfish of the Pleuronectidae family dominated during periods of higher salinity, and Cyprinids were more important when river flow was greatest (Dias et al 2012). Interestingly, and contrary to expectations, we did not find any eels *Anguilla anguilla*, which have been recorded as regular prey at other locations, such as in the Minho estuary (Dias et al. 2012) and Lagoa de Santo André (Catry et al. 2010); this may well be an indication of the increasing scarcity of this critically endangered migratory fish in Portuguese waters.

It should be noted that it is likely that our sampling through pellets underestimated small prey with small otoliths. We believe this particularly applies to sand-smelt and European anchovy, both of which are very abundant at Sado estuary in the autumn-winter period (e.g Lopes da Cunha 1994, Cabral 1999, Neves et al. 2008). On many occasions, we have observed cormorants at Sado estuary fishing in dense flocks (sometimes gathering hundreds of individuals), a technique these birds use to chase small pelagic prey (Van Eerden & Voslamber 1995). On some of those occasions we could see small pelagics (looking like sand-smelts or anchovies) jumping out of the water where cormorants were diving; gulls and terns sometimes also fished above diving cormorant flocks. Given the frequency with which we observed this kind of fishing and the large numbers of cormorants involved, we believe it is likely that small pelagics were underrepresented in pellets (note, however, that group-fishing could have targeted shoals of small mullets as well). There are other fishes that are extremely abundant in the estuary and which were not recorded, possibly for the same reason, namely the gobies *Pomatoschistus spp.* and *Gobius niger* (Lopes da Cunha 1994, Neves et al. 2008). In fact, gobies, including *Gobius niger*, are often consumed by cormorants in other regions (e.g. Liordos & Goutner 2008, Boström et al. 2012, Dias et al. 2012). We also remark that we observed cormorants capturing pipefishes *Syngnathus/Nerophis*, but this family was not detected in the pellets that we collected. Finally, we often detected soles of the genus *Solea/Pegusa*, but very small flatfishes of the genus *Arnoglossus* and *Monochirus* (both abundant at Sado; Cabral 2000, Neves et al. 2008) were only recorded in small numbers.

The estimated consumption of 314 tonnes of fish in the estuary appears impressive, but the large majority of prey consumed (such as mullets, toadfish or Senegal breams) have little or no commercial value, and are often discarded by fishermen when caught (Cabral et al. 2012). On the contrary, the main targeted human fisheries in the estuary involve cuttlefish *Sepia officinalis* and striped red mullet or surmullet, *Mullus surmuletus*, which we did not record as cormorant prey. From data in Neves et al. (2008), we estimate that the Sado standing stock of gilt-head seabreams is 4.2 tonnes, of soles is 111.6 tonnes and of seabasses is 5 tonnes, while consumption by cormorants for each group is 2.8, 14.2 and 1.9 tonnes, respectively. These figures may suggest a potential high impact on gilt-head seabreams and seabasses. However, it is highly likely that most of those fish were captured on fish-farms (where they are extremely abundant) and not on the estuary itself. Furthermore, as noted above, those large fishes likely were overrepresented in our samples.

There have been frequent complaints from Sado aquaculturists against cormorants (e.g. Garcia 2000). Fish-farms of the lower Sado in 2011 produced 164 tonnes of fish (C. Borges, Divisão de Aquicultura, DGRM). We do not have data on production per species, but it is well-known that these are mostly gilt-head seabreams, seabass and soles (Freitas et al. 2007). Hence, cormorant consumption of these species represents a very small percentage of those totals, with the possible exception of soles. However, given the abundance of wild soles on the estuary itself (see above), it seems likely that this is where those fishes were captured by cormorants.

In conclusion, there is little evidence that cormorants could be having an important economic impact on fisheries and aquaculture in the Sado estuary. However, it is important to keep in mind that this is not to say that cormorants are unimportant predators at individual fish-farms; in fact, it is plausible that cormorants may have a significant impact for some individual producers that are unable to effectively deter the birds to feed on particular ponds. It is then at those particular ponds that action must be taken to protect economic interests. Culling of individuals (which is sometimes suggested as a possible solution), on the contrary, is most unlikely to produce the desired results (Chamberlain et al. 2013).

Acknowledgements

Eng[a]. Sofia Castelo Branco Silveira, in charge of the Sado Nature Reserve (ICNF) allowed the use of the reserve boat for fieldwork. Marina Sequeira and the wardens João Francisco and Carlos Silva provided critical logistical support. Thanks are due to Dr. Henrique Cabral, Dr. Célia Teixeira (Faculdade de Ciências da Universidade de Lisboa) and Dr. Alexandra Silva (Instituto Português do Mar e da Atmosfera) for providing specimens for our fish reference collection. Dr. Cristina Borges (Direção-Geral de Recursos Naturais, Segurança e Serviços Marítimos) provided information on aquaculture production at Sado estuary and Dr.

Narcisa Bandarra (Instituto Português do Mar e da Atmosfera) information on caloric value of prey-fish. João Moura, Cristina Maldonado e Federico De Martino helped with pellet processing. We also thank Dr. Hany Alonso (CIBIO-InBIO) and Dra. Alexandra Cartaxana (Museu Nacional de História Natural e da Ciência, Lisboa) for invaluable help in the identification of fish and crustaceans, respectively. This study was funded by TROIA NATURA S.A. and Fundação para a Ciência e a Tecnologia (FCT Portugal) provided additional financial support through the strategic project UID/MAR/04292/2013 granted to MARE, UID/AMB/50017 granted to CESAM and the project IF/00502/2013/CP1186/CT0003.

References

Alonso, H., Granadeiro, J.P., Ramos, J. & Catry, P. 2013. Use the backbone of your samples: fish vertebrae reduces biases associated with otoliths in seabird diet studies. Journal of Ornithology 154: 883-886.

Assis, C.A.S. 2000. Estudo morfológico dos otólitos *sagitta*, *asteriscus*, e *lapillus* de teleósteos (Actinopterygii, Teleostei) de Portugal Continental. Sua aplicação em estudos de filogenia, sistemática e ecologia. PhD thesis, Faculdade de Ciências da Universidade de Lisboa, Lisboa.

Bandarra, M.N., Calhau, M.A., Oliveira, L., Ramos, M., Dias, M.G., Bártolo, H., Faria, M.R., Fonseca, M.C., Gonçalves, J., Batista, I. & Nunes, M.L. 2004. Composição e valor nutricional dos produtos da pesca mais consumidos em Portugal. Publicações Avulsas do IPIMAR nº 11. IPIMAR, Lisboa.

Barrett, R.T., Camphuysen, C.J., Anker-Nilssen, T., Chardine, J.W., Furness, R.W., Garthe, S., Hüppop, O., Leopold, M.F., Montevecchi, W.A. & Veit, R.R. 2007. Diet studies of seabirds: a review and recommendations. ICES Journal of Marine Science 64: 1675–1691.

Boström, M.K., Östman, Ö., Bergenius, M.A.J. & Lunneryd, S.-G., 2012. Cormorant diet in relation to temporal changes in fish communities. ICES Journal of Marine Science 69: 175–183.

Boyd, I., Wanless, S. & Camphuysen, C.J. 2006. Top predators in marine ecosystems. Their role in monitoring and management. Conservation Biology Series 12. Cambridge University Press. Published in association with the Zoological Society of London.

Bregnballe, T., Goss-Custard, J.D. & Durell, S.E.A. le V dit 1997. Management of cormorant numbers in Europe: a second step towards a European conservation and management plan. In: van Dam C & Asbirk S (eds) Cormorants and Human Interests. IKC natuur beheer, Wageningen. pp 62-122.

Brito PJ 2009. Impactos da elevação do nível médio do mar em ambientes costeiros: O caso do estuário do Sado. Tese de Doutoramento, Faculdade de Ciências de Lisboa.

Cabral, H.N. 1999. Ictiofauna do estuário do Sado. Relatórios científicos e técnicos, 47. Instituto de Investigação das Pescas e do Mar, Lisboa.

Cabral, H.N. 2000. Distribution and abundance patterns of flatfishes in the Sado Estuary, Portugal. Estuaries 23: 351-358.

Cabral, H., Laborde, M., Gamito, R., Ferreira, P. & Solanou, M. 2012. Caracterização da actividade da pesca no estuário do Sado e avaliação de potenciais impactos na população de roazes. Relatório do Centro de Oceanografia da Faculdade de Ciências da Universidade de Lisboa, Lisboa.

Carss, D.N. 1997. Techniques for assessing Cormorant diet and food intake: towards a consensus view. Supplementi di Ricerchi Biologia Selvaggina XXVI: 197–230.

Catry, P., Costa, H., Elias, G. & Matias, R. 2010. Aves de Portugal. Ornitologia do Território Continental. Assírio & Alvim, Lisboa.

Chamberlain, D.E., Austin, G.E., Newson, S.E., Johnston, A. & Burton, N.H.K. 2013. Licensed control does not reduce local cormorant *Phalacrocorax carbo* population size in winter. Journal of Ornithology 154: 739–750.

Cramp, S. & Simmons, K.E.L. (eds) 1977. The Birds of the Western Palearctic, vol. I. Oxford University Press, Oxford.

Dias, E., Morais, P., Leopold, M., Campos, J. & Antunes, C. 2012. Natural born indicators: great cormorant *Phalacrocorax carbo* (Aves: Phalacrocoracidae) as monitors of river discharge influence on estuarine ichthyofauna. Journal of Sea Research 73: 101–108.

Freitas, D., Gomes, J., Sales-Luís, T., Madruga, L., Marques, C., Baptista, G., Rosalino, L.M., Antunes, P., Santos, R. & Santos-Reis, M. 2007. Otters and fish farms in the Sado estuary: Ecological and socio-economic basis of a conflict. Hydrobiologia 587: 51-62.

Garcia, G.M.D. 2000. A população de corvos-marinhos-de-faces-brancas *Phalacrocorax carbo* na Reserva Natural do estuário do Sado. Relatório para o ICN/Reserva Natural do estuário do Sado, Setúbal.

Grade, N. 1996. Ecologia alimentar e efectivo invernante do corvo-marinho-de-faces-brancas *Phalacrocorax carbo*, no Parque Natural da Ria Formosa – Interacções com as pisciculturas intensivas e semi-intensivas. Bachelor's thesis, Universidade do Algarve.

Grade, N. & Granadeiro, J. P. 1997. Cormorant wintering in Portugal: the case of Ria Formosa Natural Park. Supplementi di Ricerchi Biologia Selvaggina XXVI: 465-468.

Grémillet, D., Wright, G., Lauder, A., Carss, D.N. & Wanless, S. 2003. Modelling the daily food requirements of wintering great cormorants: a bioenergetics tool for wildlife management. Journal of Applied Ecology 40: 266-277.

Karpouzi, V.S., Watson, R. & Pauly, D. 2007. Modelling and mapping resource overlap between seabirds and fisheries on a global scale: a preliminary assessment. Marine Ecology Progress Series 343: 87-99.

Leopold, M.F., van Damme, C.J.G., van der Veer, H.W. 1998. Diet of cormorants and the impact of cormorant predation on juvenile flatfish in the Dutch Wadden Sea. Journal of Sea Research 40: 93–107

Lilliendahl, K. & Solmundsson, J. 2006. Feeding ecology of sympatric European shags *Phalacrocorax aristotelis* and great cormorants *P. carbo* in Iceland. Marine Biology 149: 979–990.

Liordos, V. & Goutner, V. 2008. Habitat and temporal variation in diet of great cormorant nestlings in Greek colonies. Waterbirds 31: 424-437.

Lopes da Cunha, P. 1994. Estrutura e dinâmica da ictiofauna do estuário do Sado. PhD thesis, Universidade de Lisboa.

Neves, A., Cabral, H., Figueiredo, I., Sequeira, V., Moura, T. & Gordo, L.S. 2008. Fish assemblage dynamics in the Tagus and Sado estuaries (Portugal). Cahiers Biologie Marine 49: 23-35

Prenda, J. & Granado-Lorencio, C. 1992. Claves de indentificacion de *Barbus bocagei*, *Chondrostoma polylepis*, *Leuciscus pyrenaicus* y *Ciprinus carpio* mediante algunas de sus estruturas oseas. Doñana, Acta Vertebrata 19: 25-36.

Prenda, J., Freitas, D., Santos-Reis, M. & Collares-Pereira. M.J. 1997. Guía para la identificación de restos óseos pertecientes a algunos peces comunes en las aguas continentales de la Península Ibérica para el estúdio de la dieta de depredadores ictiófagos. Doñana, Acta Vertebrata 24: 155-180.

Tuset, V.M., Lombarte, A. & Assis, C.A. 2008. Otolith atlas for the western Mediterranean, north and central eastern Atlantic. Scientia Marina 72S1: 7-198.

Ridgway, M.S. 2010. A review of estimates of daily energy expenditure and food intake in cormorants *(Phalacrocorax spp.)*. Journal of Great Lakes Research 36: 93-99.

Suter, W. 1997. Roach rules: shoaling fish are a constant factor in the diet of cormorants *Phalacrocorax carbo* in Switzerland. Ardea 85: 9-27.

Stewart, D.C., Middlemas, S.J., Gardiner, W.R., Mackay, S. & Armstrong, J.D. 2005. Diet and prey selection of cormorants *(Phalacrocorax carbo)* at Loch Leven, a major stocked trout fishery. Journal of Zoology 267: 191–201.

Van Eerden, M.R. & Voslamber, B. 1995. Mass fishing by cormorants *Phalacrocorax carbo sinensis* at Lake Ijsselmeer, the Netherlands: a recent and successful adaptation to a turbid environment. Ardea 83: 199-212.

Veen, J., Mullié, W.C. & Veen, T. 2012. The diet of the White-breasted Cormorant *Phalacrocorax carbo lucidus* along the Atlantic coast of West Africa. Ardea 100: 137-148.

Votier, S.C., Bearhop, S., MacCormick, A., Ratcliffe, N., Furness, R.W. 2003. Assessing the diet of great skuas, *Catharacta skua*, using five different techniques. Polar Biology 26: 20–26.

Yoda, K., Tajima, T., Sasaki, S., Sato, K. & Niizuma, Y. 2012. Influence of local wind conditions on the flight speed of the great cormorant *Phalacrocorax carbo*. International Journal of Zoology Article ID 187102. doi:10.1155/2012/187102

Zijlstra, M. & Van Eerden, M.R. 1995. Pellet production and the use of otoliths in determining the diet of cormorants *Phalacrocorax carbo sinensis*: trials with captive birds. Ardea 83: 123-131.to decreasing bird migration distances. Global Change Biology 15: 1859-1865.