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ORIGINAL PAPER

Prey choice and ingestion of microplastics by common shelducks and common eiders in the Wadden Sea World Heritage Site

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Abstract

Top predators such as coastal birds are essential components of marine food webs, and understanding their trophic interactions forms an essential basis of food web models. At the same time, the proportion of plastic debris in marine food webs has constantly increased while the degree of plastic ingestion by marine birds is still poorly known. In this study, the diets and microplastic uptakes in two numerous benthivorous bird species in the Wadden Sea were examined microscopically, i.e. the common eider (*Sommateria mollissima*) indicative for the subtidal and the common shelduck (*Tadorna tadorna*) indicative for the intertidal area. Eiders ($n = 42$ carcasses; $n = 120$ faecal samples) mainly ingested common cockles (*Cerastoderma edule*). Blue mussels (*Mytilus edulis*) ranged second and—same as the invasive razor clam (*Ensis leei*)—occurred more frequently than reflected by historic data. Proportions of gastropods, bristle worms and crustaceans were low. Shelducks ($n = 20$ carcasses; $n = 98$ faecal samples) fed mainly on small molluscs, especially *C. edule*, mud snails *Peringia ulvae*, and amphipods. Plastic debris was found in 92.9% of the stomachs and 74.2% of the faeces from eiders as well as in 95% of the stomachs and 85.7% of the faeces from shelducks. Filaments in shelduck prey remains were significantly larger, whereas there was no species-specific difference in abundance of filaments. Most plastic consisted of brightly coloured filaments ˂ 5 mm. These findings indicate regular uptake and excretion of plastic debris by coastal benthivorous seabirds, both in the subtidal and intertidal realm. The origin and mode of uptake of microplastics are discussed.

Keywords Food choice · Seabird · Contamination · North Sea · Benthos

Introduction

Understanding the link between a predator and its prey is not only important for describing the function of a given species in the marine ecosystem, but also provides vital information for food web models (e.g. Baird et al. 2009; De la Vega et al. 2018; Horn et al. 2019). Furthermore, such knowledge is crucial to support management and conservation policies, especially of protected species. Seabirds and coastal birds are essential top predators in marine ecosystems, with important effects on the food web (e.g. Horn et al. 2019). Due to their high trophic levels, they react sensitively to system changes and are thus suitable bioindicators, both for changes in the food web (e.g. Furness and Camphuysen 1997; Horn et al. 2019) as well as for its contamination by plastics (Lourenço et al. 2017; Provencher et al. 2018). Numbers of common eiders (*Sommateria mollissima,* hereafter eiders) and common shelducks (*Tadorna tadorna,* hereafter shelducks) along the East Atlantic Flyway are high (BirdLife International 2023), however, peak numbers can be found in the international Wadden Sea World Heritage Site which serves as a significant wintering resting and moulting area for both species during certain times of the year (Garthe et al. 2007; Kleefstra et al.2022; Kempf and Kleestra 2013). Given the high abundance of both species, it is essential to understand their roles in the marine food web in the Wadden Sea. This includes their impacts on benthic communities in the subtidal and intertidal zones, respectively. Furthermore, their function as top-predators makes them suitable indicators of plastic contamination of the marine food web (Provencher et al. 2019).

Almost the entire East Atlantic Flyway population of shelducks uses the Wadden Sea area, i.e. > 200,000

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individuals annually, especially during the moulting period (Kleefstra et al. 2022). A major roosting site of moulting birds is located in the south-eastern part of the Wadden Sea area, in the federal state of Schleswig–Holstein, Germany (Kempf and Kleestra 2013; Kleefstra et al. 2022). Previous studies outside of the main moulting areas found that shelducks fed primarily on small molluscs, notably mudsnails (*Peringia ulvae*), and on crustaceans, but also consumed plant material by sieving water and sediment through the serrated lamellae of their bill (Viain et al. 2013). The mud shrimp (*Corophium volutator*) has also been reported as an essential prey species in the Dutch Wadden Sea (Kraan et al. 2006). However, up-to date information on the prey choice of shelducks in their core moulting area in the Wadden Sea is still greatly lacking.

Up to 200,000 eiders can be found in the international Wadden Sea and 60,000 in the region of Schleswig–Holstein, although numbers in the Wadden Sea area have recently been decreasing (Garthe et al. 2007; Kleefstra et al. 2022). Eiders have been described to feed on a wide variety of molluscs, crustaceans, echinoderms, fish, and other taxa across their range (Waltho and Coulson 2015; Laursen and Møller 2022). About 30 years ago, four main prey species of eiders have been identified in the south-eastern Wadden Sea, with common cockles (*Cerastoderma edule*) making up 75% of the eiders' diet, while the remaining 25% mainly consisted of blue mussels (*Mytilus edulis*), Baltic tellin (*Limecola balthica*), and shore crabs (*Carcinus maenas*; Nehls 1991; Nehls and Ketzenberg 2002). A recent study from the Danish waters highlighted the increasing importance of the invaded razor clam (*Ensis leei*) (Laursen and Møller 2022). However, in the south-eastern Wadden Sea, up-to date knowledge on the prey choice of eiders in the light of newly invaded benthic species is currently lacking (Baird et al. 2012; Reise et al. 2006). Therefore, recent information on potential altered prey choice in light of climate change and invaded species is urgently missing to provide a baseline for food web models and conservation management.

Microplastics, referring to plastic debris < 5 mm (Arthur et al. 2009), have only been identified as an environmental issue within the last 20 years, and their impact remains poorly understood (Lourenço et al. 2017; Provencher et al. 2018). The impact of larger items of marine litter seems more obvious, such as entanglement of marine animals in ghost nets (Andrady 2011; Bullimore et al. 2001) or ingestion of macroplastics (plastic debris > 20 mm) leading to starvation (Kühn and van Franeker 2020; Andrady 2011; Van Franeker et al. 2011). About 50% of seabirds are known to be affected by marine debris as a result of entanglement or consumption (Kühn and van Franeker 2020). However, although ingestion of plastics has been recorded for a variety of aquatic organisms, information on the movements and fate of plastics within food webs is still lacking (Provencher et al. 2019). For example, few studies have discussed the trophic transfer, retention, biomagnification and accumulation or excretion of microplastics (Provencher et al. 2019). Microplastic contamination has been reported for many of the expected prey species of eiders and shelducks in the Wadden Sea (Fischer 2019; Leslie et al. 2013), and has generally been found in biota across many trophic levels (Provencher et al. 2019). Therefore, it was aimed to assess the degree of ingestion of microplastics by both study species. As the degree of contamination was expected to differ between the subtidal and intertidal zones due to differences in current velocities, wind and wave exposure, particle sizes and sedimentation rates (Mendes et al. 2021; Markic et al. 2023), we hypothesised that the degree of microplastic uptake as well as microplastic size would differ considerably between the two species, reflecting differences in the degree of contamination among the two habitat types. Furthermore, it was expected that simultaneously investigating prey choice and microplastic uptake in these two benthivorous top predator species with different feeding behaviours (i.e. filter-feeding of small organisms with high contact with the sediment in the intertidal zone by shelducks, and digging and picking up prey from the sea bed by diving in the subtidal zone by eiders) would allow to draw conclusions about the sources, transfer, and fate of microplastics at a high trophic level.

The main aim of the present study is to provide up-to-date data on the food choices of shelducks and eiders in the south-eastern Wadden Sea area, which includes essential proportions of the European populations of both species. Finally, we hypothesised that the two species would show different rates of microplastic ingestion, reflecting the contamination in their main habitat types (i.e. the subtidal and the intertidal zones). Potential sources and modes of uptake of plastic debris by marine birds are discussed.

Materials and methods

Study site and samples

Overall, 42 eider and 20 shelduck carcasses were collected from different locations along the North Sea coast of Schleswig–Holstein and used in this study (Table 1, Fig. 1). Most birds were found on beaches and had died of unknown causes, apart from four shelducks and one eider that were collected after colliding with a lighthouse or in traffic, respectively. Two other shelducks were also considered likely to have died as a result of trauma, indicated by severe internal organ damage and internal bleeding. The eiders were found between 2011 and 2016 and the shelducks between 2008 and 2018. Additionally, 120 faecal samples from eiders on a known roost of eiders at a sandbank near Blauortsand (54°10′26.5N, 8°40′13.8E) were collected in

Table 1 Overview of samples for stomach content analysis of eider and shelduck carcasses

Species	Sex	Age	Species-specific season	Number
Eider (*n* = 42)	Female	1cy	Fall/migration	2
		Adult	Fall/migration	1
	Male	2cy	Winter	1
		Adult	Spring/migration	10
			Summer/breeding	5
			Fall/migration	13
			Winter	10
Shelduck (*n* = 20)	Female	1cy	Fall/migration	1
		2cy	Spring/migration—Summer/breeding	1
		Adult	Spring/migration—Summer/breeding	2
			Fall/migration	2
			Winter	2
	Male	1cy	Fall/migration	1
		Adult	Spring/migration—Summer/breeding	5
			Fall/migration	4
			Winter	2

Age of the birds are given as 1cy = first calendar year, 2cy = second calendar year, and adult. Species-specific seasons for eiders were spring/migration: 01.03–30.04, summer/breeding: 01.05–31.08, fall/migration: 01.09–30.11, and winter: 01.12–29.02 (according to Garthe et al. 2007), and for shelducks were spring/migration to summer/breeding: 01.03–30.06, fall/migration: 01.07–31.10, and winter: 01.11–29.02 (Cimiotti et al. 2022; D Cimiotti, FTZ, pers. comm.)

July 2016, and 49 faecal samples each year from shelducks on the North Frisian island of Trischen in the summers of 2018 and 2019, respectively. Faecal samples were scraped carefully from the surface and moved into small plastic boxes. The collection of sediment attached to the faeces was avoided as far as possible.

Processing and analysis of samples

The bird carcasses were dissected following a standardized protocol (cf. Camphuysen 2007; Camphuysen and Van Franeker 2007; Schwemmer et al. 2012), including macroscopic assessment of body condition and organ health. The birds were initially inspected externally, and biometric data, sex, state of moult, state of decomposition on a six-stage scale, and completeness on a four-stage scale were documented. The cause of death was determined whenever possible. After opening the body, the intestinal and subcutaneous fat as well as pectoral muscle condition was classified on a four-stage scale ranging from 0 = no fat/strongly emaciated to 3 = very fat/good condition, following van Franeker and Camphuysen (2007). The sum was used to classify the overall condition index ranging from “mortally emaciated” (0–1), “critically emaciated” (2–3), “moderate body condition” (4–6), and “good body condition” (7–9) (van Franeker and Camphuysen 2007). Organ health was determined macroscopically for liver, lung, kidney, and gut, using a four-stage scale ranging from 0 = heavily infected to 3 = pristine. Same as for body condition, the sum of these scores was computed to classify the overall organ health (see above) (Camphuysen and Van Franeker 2007). The organ index could not be calculated for two eiders, in which the intestines were partially missing due to scavengers, and one shelduck, because of severe pathological lesions. These individuals were excluded from subsequent statistical analyses.

For diet analysis, the birds’ stomachs were removed and frozen at − 20 °C until dissection. The contents were thawed and then got rinsed over a 300 µm sieve and preserved in ethanol. Faecal samples were stored at − 20 °C and then dried for 3 days at 50 °C prior to analysis.

The degree of stomach filling was estimated visually by comparison with ten reference samples from eiders obtained from gillnet bycatches in the Baltic Sea. These eiders died during feeding and had full stomachs, while three also had full sublingual pouches. The stomach contents of the study birds were therefore categorized as nearly empty (containing only few residues of prey organisms, 1–5% full in relation to reference samples), little-filled (6–30%), moderately filled (31–70%), and well-filled (˃70%). To confirm the reliability of using stomach contents from beached birds to determine the birds’ diet, the physical condition, state of decomposition, and degree of stomach filling (compared to drowned birds) were correlated.

All the samples were analysed using a stereomicroscope (Olympus SZX9, Germany) with a magnification of 7.9–71. The remains of organisms were identified to species level or to the closest taxonomic level possible using a reference collection or suitable literature (e.g.

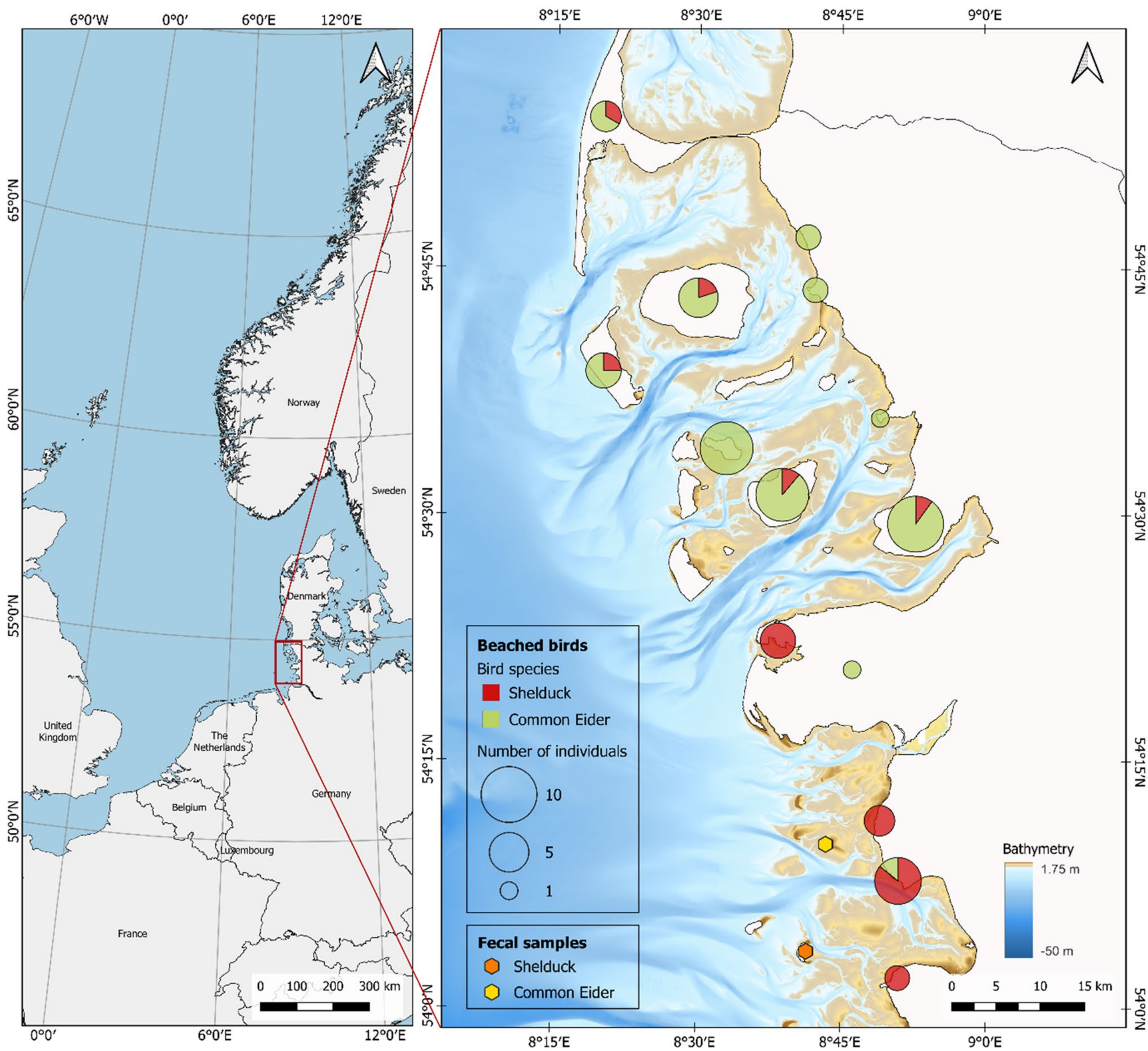

Fig. 1 Study area with locations of collected carcasses and sampling locations of faeces

Härkönen 1986; Hartmann-Schröder 1996; Hayward and Ryland 1990). Prey and other items, such as plant material, were noted as present or absent. Plastic debris was categorized as filaments or fragments, counted and their lengths were measured to the nearest 0.1 mm for filaments and 0.05 mm for fragments. A subset of the filaments < 1 mm was analysed by Fourier transform infrared spectroscopy (FTIR). As it has been shown that differently coloured plastic fragments might influence the chance of ingestion (see review of Provencher et al. 2017), their colour was recorded.

Statistical analysis

To test for differences in the degree of stomach filling between eiders and shelducks Mann–Whitney-*U* Test was used (Lepš and Šmilauer 2020). Subsequently the rank-based Kruskal–Wallis Test was used to test the influence of the state of decomposition, body and organ health index on the degree of stomach filling (Lepš and Šmilauer 2020). Finally, we tested for differences of the overall abundance and for differences in length of plastic filaments among the two study species and the two sample types (i.e. stomach contents vs. faeces) using Generalized Linear Mixed Effect Models (GLMMs; Venables and Ripley 2002). For this, sample type and species were used as fixed effects, while the sample ID was included as random intercept. All statistical tests were performed using R Version 4.0.3 (R Core Team 2020).

Results

Applicability of beached birds for diet analysis

None of the birds' stomachs were completely empty, and even among those categorized as nearly empty, including 12 eiders (28.6%) and 5 shelducks (25%), most contained more than 1 prey species. Most stomachs, including 22 eiders (52.4%) and 12 shelducks (60%), were classified as little-filled, while stomachs from 6 eiders (14.3%) and 3 shelducks (15%) were moderately filled. Only two eider stomachs (4.8%) were categorized as well-filled. The body condition of the birds was generally poor, and 40 eiders (95.2%) and 14 shelducks (70%) were considered to be mortally or critically emaciated. Two individuals of each species (4.8% of eiders, 10% of shelducks) had moderate body condition and four shelducks (20%) had good body condition. However, despite the overall poor body condition, most eiders ($n=29$; 72.5%) and shelducks ($n=13$; 68.4%) had an organ-condition index ≥ 9 (out of a maximum score of 12). The four shelducks that collided with a lighthouse and the two assumed-collision victims were all in moderate or good physical condition. Body decomposition was not advanced in eiders (mean 4.48 out of a maximum score of 6) as well as for shelducks (4.75). There was no significant difference between the two species in terms of the probability of the stomach being nearly empty ($n=17$; 27.4%), little-filled ($n=33$; 53.2%), moderately full ($n=10$, 16.1%), or well-filled ($n=2$, 3.2%) (Mann–Whitney-U-Test, $W=409.5$, $p=0.868$). Therefore, the influences of organ-condition index, body-condition index, and state of decomposition on the degree of stomach filling were examined for eiders and shelducks jointly, using the Kruskal–Wallis test. The degree of stomach filling was not significantly related to the state of decomposition (Chi-square test, $\chi^2=3.15$, $df=3$, $p=0.369$), body-condition index (Chi-square test, $\chi^2=7.20$, $df=7$, $p=0.408$), or organ-condition index (Chi-square test, $\chi^2=5.69$, $df=8$, $p=0.681$).

Common eiders

Analysis of stomach contents and faeces of the eiders from the Wadden Sea revealed a diverse composition of 14 different prey items that could be determined to species level, as well as 19 types of prey that were identified to genus or higher taxon level (Table 2). Overall, 83.1% of both sample types contained more than one type of prey and 75.3%

Table 2 Diet composition of eiders and shelducks presented as relative frequencies of prey species and other types of items

	Eider		Shelduck	
	Stomach	Faeces	Stomach	Faeces
	$n=42$	$n=120$	$n=20$	$n=98$
Bivalves total	100	100	85	98
Bivalvia sp.	4.8	34.2	5	23.5
Mytilus edulis	69.1	43.3	15	27.6
Ensis sp.	9.5	17.5	–	–
Limecola balthica	4.8	47.5	45	30.6
Cerastoderma edule	73.8	99.2	85	98
Donax vittatus	–	2.5	–	–
Pholadidae sp.	–	1.7	–	–
Petricola pholadiformis	–	2.5	–	–
Barnea candida	–	1.7	–	–
Scrobicularia plana	–	2.5	–	–
Spisula sp.	–	4.2	–	1
Mya arenaria	–	4.2	–	7.1
Gastropods total	38.1	40	95	83.7
Gastropoda sp.	2.4	1.7	5	–
Littorina sp.	7.1	2.5	–	–
Littorina littorea	9.5	–	5	–
Littorina saxatilis	–	–	–	2
Peringia ulvae	35.7	36.7	90	83.7
Crepidula fornicata	–	0.8	–	–
Bristle worms total	7.1	19.2	30	16.3
Polychaeta sp.	–	18.3	–	5.1
Nereididae sp.	2.4	–	30	12.2
Pectinaria sp.	–	0.8	5	–
Lanice conchilega	4.8	–	–	1
Crustaceans total	23.8	27.5	25	32.7
Crustacea sp.	2.4	–	–	–
Balanidae sp.	14.3	15.8	20	11.2
Brachyura sp.	2.4	11.7	–	4.1
Carcinus maenas	11.9	1.7	5	2
Liocarcinus sp.	2.4	–	5	1
Crangon crangon	–	–	5	–
Ostracoda sp.	–	1.7	–	3.1
Amphipoda sp.	2.4	0.8	–	18.4
Insects total	–	1.7	–	2
Insecta sp.	–	0.8	–	–
Plecoptera sp.	–	0.8	–	–
Formicidae sp.	–	-	–	1
Coleoptera sp.	–	-	–	1
Fish total	2.4	3.3	–	2
Osteichthyes sp.	2.4	2.5	–	1
Synggnathus sp.	–	0.8	–	–
Clupeidae sp./Osmerus sp.	–	–	–	1
Plant material	59.5	30.8	50	37.8

Prey species were additionally summed up within their taxonomic groups contained two to five different components (Fig. 2a). A maximum of nine different types of prey were found in two cases (Fig. 2a). Bivalves were found in all eider samples, with *C. edule* being the most common prey item overall (Fig. 2b, Table 2). Other frequently found bivalves included *M. edulis*, *L. balthica*, and *Ensis sp.* (Table 2). Two terrestrial prey items were found, including one unidentified insect and one stonefly *Plecoptera sp.* (Fig. 2b, Table 2). Plant material occurred regularly, and had probably been consumed unintentionally together with the prey organisms (Fig. 2b, Table 2).

Common shelducks

Shelduck samples included 11 prey species and 15 types of prey identified to genus or higher taxon level, indicating a lower diversity of prey items in the shelduck samples compared with the eider samples (Table 2). Overall, 93.3% of the samples contained between two and eight different types of prey, and 76.3% contained between two and five different components (Fig. 3a). Most samples included *C. edule* and *P. ulvae* with similar frequencies, followed by *L. balthica* (31% in faeces and 45% in stomach contents; Table 2). Amphipods and bristle worms were also frequently found. *Crangon crangon* was one of the most common prey items in one shelduck stomach sample, with 25 individuals

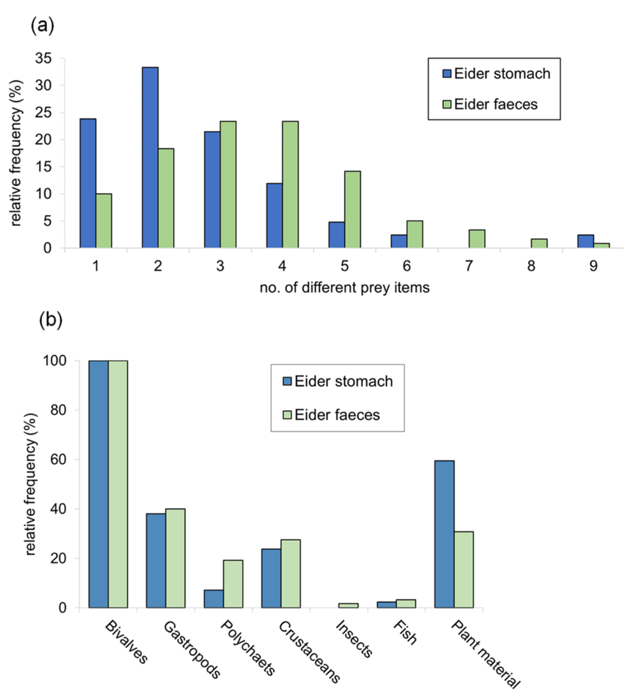

Fig. 2 Frequency distributions of number of different prey items per sample in eiders, excluding plant material (**a**), and relative frequencies (proportions of samples including the respective prey type on the total of all samples) of taxonomic groups of prey organisms in diet samples from eiders (**b**)

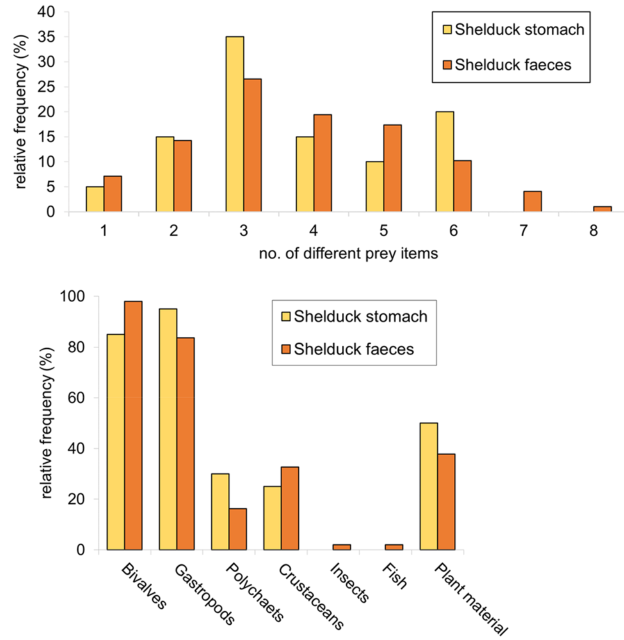

Fig. 3 Frequency distributions of number of different prey items per sample in shelducks, including plant material, which is known to be part of their diet (**a**), and relative frequencies (proportions of samples including the respective prey type on the total of all samples) of taxonomic groups of prey organisms and plant material in diet samples from shelducks (**b**)

(Table 2). The only insects, including remains of one ant and one beetle, were found in droppings (Fig. 3b, Table 2). Two fish remains were found, including one that was identified as close to *Clupeidae sp.* or *Osmerus sp.* (Fig. 3b, Table 2). Plant material or algae occurred in 50% of stomach samples and 37.8% of faecal samples (Fig. 3b, Table 2).

Faeces vs. stomach contents

The two most important prey groups, bivalves and gastropods, occurred with similar frequencies in both sample types in both species; however, the frequencies of polychaetes and crustaceans were more variable (Fig. 2b, Fig. 3b, Table 2). Overall, prey diversity was higher in faecal samples in both species, with 18 different prey items in stomachs compared with 27 in faeces in eiders and 13 different prey items in stomachs compared with 20 in faeces in shelducks (plant material excluded; Table 2). Most notably, six species and one genus of bivalves were found exclusively in faeces in eiders (Table 2). Other types of prey that occurred exclusively in faecal samples in both species were ostracods and insects. In contrast, plant material was less frequent in faecal samples (Fig. 2b, Fig. 3b, Table 2). No significant difference in occurrence and length of microplastics among the two sample types were found.

Occurrence of plastic debris

Plastic debris was detected in all the investigated sample groups, including 92.9% of stomach and 74.2% of faecal samples from eiders and 95% of stomach and 85.7% of faecal samples from shelducks. Occurrence of plastics did not differ significantly among the two species (GLMM: $z = -0.02$, $p = 0.99$) nor among sample type (i.e. stomach and faeces samples; GLMM: $z = 0.35$, $p = 0.73$). We found no differences in length of plastic debris among sample types (GLMM: $z = -1.15$, $p = 0.25$), but significantly longer particles in shelducks compared to eiders (GLMM: $z = -2.64$, $p < 0.01$). Plastics in shelducks extended the length of plastics in eiders by the factor 0.84. Most plastic items were filaments < 5 mm, often brightly coloured, and were thus assigned as microplastics (Fig. 4). To validate the nature of the filaments found in this study, we performed an FTIR analyses. However, due to the small diameter of the fibres, it was not possible to receive definitive results. The spectra indicated that the filaments were likely polyamides with a protein coating, but no further results could be obtained. A total of 1417 filaments were found, ranging from 0.1 to 22.5 mm (Fig. 5). Filaments < 1 mm had a share of 17.5% of the total of all filaments found in common eider and in 13.9% of the filaments found in shelduck samples, while the largest proportion of filaments fell into the category of 1–5 mm length (74.2% in common eider and 75.8% in shelducks; Fig. 5). A total of 8.3% of the filaments found in common eider and 10.3% found in shelduck samples were > 5 mm and, therefore, considered mesoplastics (Fig. 5). In addition to plastic filaments, the only other type of plastic debris was fragments ranging from 0.05 × 0.05 mm to 1.5 × 1.5 mm. Fragments occurred less frequently than filaments, accounting for 3.1% of all microplastics found. In terms of colour, filaments ranged from colours such as black (38%), transparent (32.5%), blue (17.1%), and red (8.8%), to rarer colours like orange (1.3%), yellow (1.3%), green (0.5%), pink (0.3%), and lilac (0.2%) with no obvious difference between the two species and sample types. Fragments were often multicoloured, including various combinations of two or three different colours.

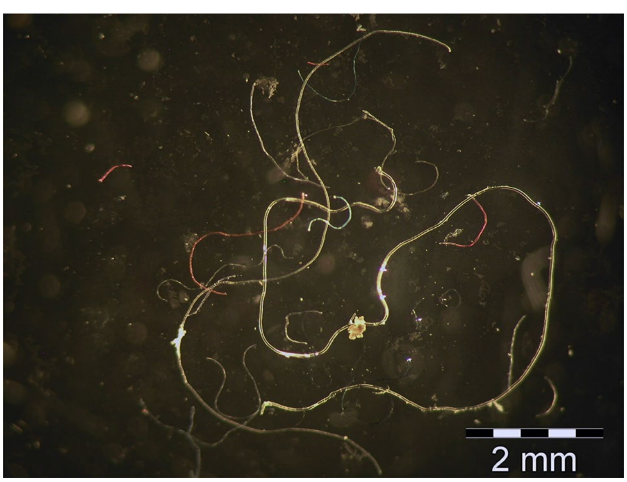

Fig. 4 Microplastic filaments found in a stomach sample from a shelduck

Discussion

Diet analysis

Stomach and faecal samples from eiders and shelducks revealed an almost exclusively marine diet, consisting mainly of molluscs, accompanied by crustaceans, polychaetes, and occasional fish and insects. The current results partially confirmed the types of prey previously described in the literature (see below). In contrast, however, also plants and algae were detected in many samples, although their importance as food sources for shelducks remains questionable given that it was not possible to demonstrate their intentional uptake. It was also unclear if the insects found in faecal samples from both species comprised part of the bird's diet, or had contaminated the samples after deposition. On the other hand, however, insects have been found in other diet studies for both species (Glutz von Blotzheim and Bauer 1992; Oelke 1979).

The differences in frequencies of prey and diversity of prey species between the stomach and faecal samples were probably the result of the different locations, given that the faecal samples were only collected from one location while the carcasses were obtained from various locations. In addition, the higher number of faecal samples may have revealed a higher diversity. The relative frequencies of prey species need to be interpreted carefully, given that prey items may have different levels of digestibility and the remains may thus have different retention times (Barrett et al. 2007). For example, crab claws take longer digest and excrete than shell fragments of molluscs, and crabs may thus be overestimated in diet analyses (Glutz von Blotzheim and Bauer 1992). On the other hand, some invertebrates, such as gelatinous zooplankton like scyphozoans, salps, hydrozoans, and ctenophores, are digested quickly and leave few or no traces (McInnes et al. 2017), and these types of prey can thus only be detected with traditional dietary sampling methods if the bird dies suddenly after foraging. Oelke (1979) and Swennen (1976) analysed the diet of shot birds and found hydrozoans in the stomach contents of both shelducks and eiders.

In contrast to the previous finding that eiders feed mainly on one prey species at a time and their faeces, therefore, usually contain only one type of prey (Nehls 1991; Swennen 1976), most of the samples analysed in this study contained a variety of prey organisms.

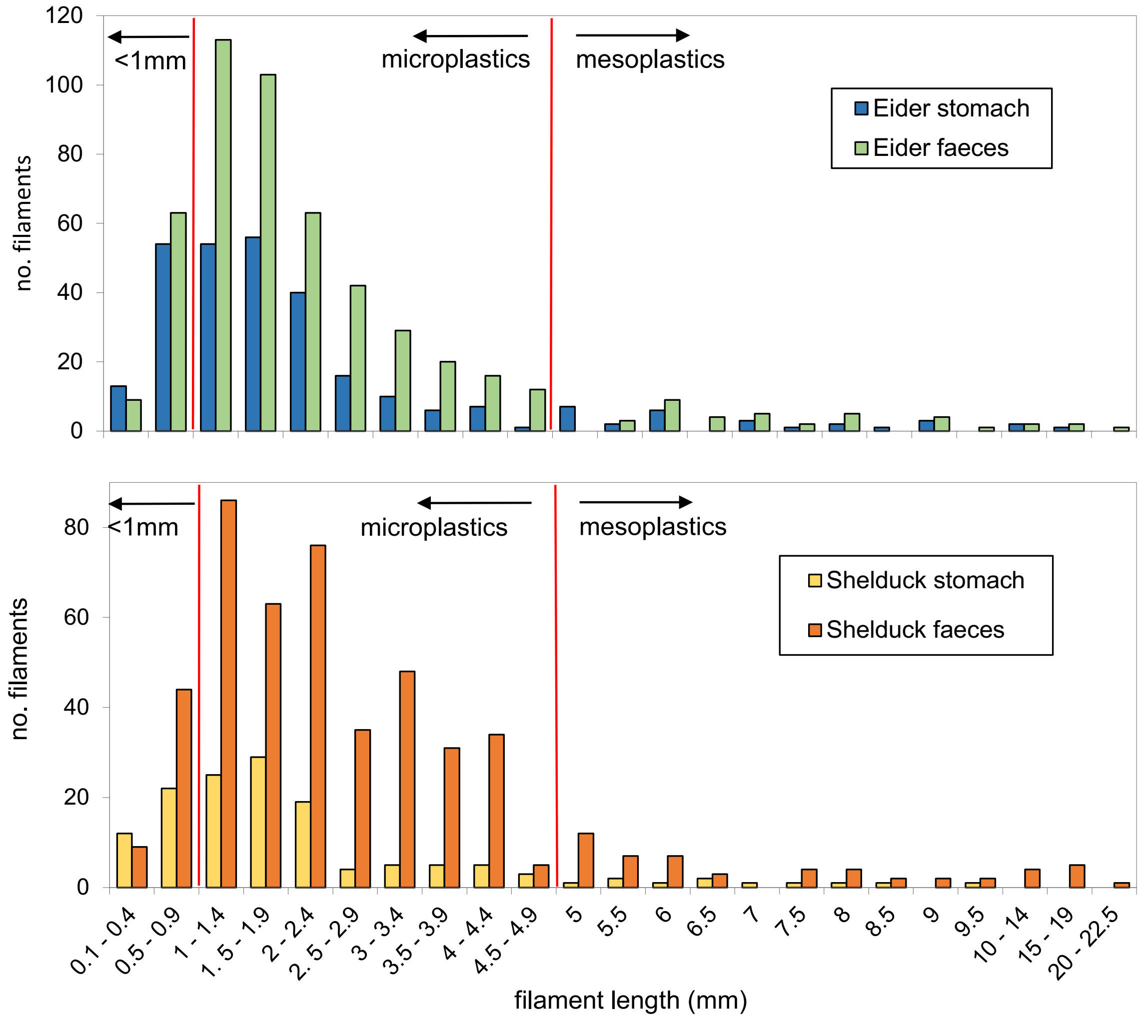

Fig. 5 Frequency distribution of length of microplastic and mesoplastic filaments found in the diet samples from **a** eiders and **b** shelducks

Common eider diet

Our study indicates that the importance of blue mussels as prey for common eiders in the south-western Wadden Sea has increased compared with data from the late 1980s, whereas the level of common cockles was still comparably high (Nehls 1991). According to a recent study, common eiders made much less use of common cockles in the northern Wadden Sea (Laursen and Møller 2022) as compared to the south-eastern part (this study). Further regional differences are highlighted by a frequent use of *Spisula subtruncata* in the Dutch Wadden Sea (Leopold 1996; Leopold et al. 2001), while *Spisula sp.* only occurred rarely in samples in the current study. While the invasive razor clam was absent in the south-eastern Wadden Sea during the 1990s (Nehls 1991; Nehls and Ketzenberg 2002), this species now occurred regularly in the samples and reached comparable frequencies as in the northern Wadden Sea (Laursen and Møller 2022). The high flesh-to-shell ratio makes this species a high-energy prey item for benthivorous diving duck species (Schwemmer et al. 2019) which likely explains its increasing importance.

Although Nehls and Ketzenberg (2002) found a preference for *M. edulis*, and the authors stated that eiders would switch to *C. edule* due to limitations on the mussel beds of *M. edulis*, a diet consisting of only one or two species may not be advantageous: Eiders are limited in terms of their antioxidant levels as a result of food limitations, and certain types of prey were found to increase their antioxidant levels (Møller et al 2019). Eiders may thus select types of prey other than cockles or blue mussels. In accordance with this, very small prey species of little nutritional value were also found frequently, such as *P. ulvae*, and less commonly ostracods and amphipods. The high percentage of crustaceans in our study was largely attributable to commonly found barnacles, and was, therefore, likely to represent a “bycatch” consumed while foraging on molluscs. Notably, the current study did not find some types of prey previously identified by Glutz von Blotzheim and Bauer (1992), including Echinodermata, Anthozoa, Lepadidae, and Coleoidea, as well as fish and mollusc spawn.

Common shelducks diet

Shelduck diet generally comprised small-sized benthic organisms, with a few species being very common in many samples. *P. ulvae* (Oelke 1979; Viain et al. 2013) and *C. edule* (Glutz von Blotzheim and Bauer 1990; Nehls et al. 1992) are thought to be key prey species for shelducks in the Wadden Sea, with *L. balthica* also playing a major role (Goethe 1961; Nehls et al. 1992). In the present study, *P. ulvae* and *C. edule* occurred with similar frequencies, but *C. edule* formed the largest mass of prey remains. Anders et al. (2009) indicated that *P. ulvae* was not energetically profitable as a food source and contributed little to the energy requirements of shelducks, unless it was present in extremely large densities. Live *P. ulvae* were even found in shelduck faeces, showing that they could survive the digestion process, while repair scars on the shells indicated unsuccessful attempts at digestion (Cadeé 2011). *P. ulvae* was the dominant prey item in some samples and is known to be extremely abundant in the Wadden Sea, accounting for 8% of the macrozoobenthos biomass in the north-eastern Wadden Sea (Drent et al. 2017); however, its profitability as a food source for shelducks remains to be seen. Small crustaceans can also be a locally important food source, as shown in the Dutch Wadden Sea, where *C. volutator* was the exclusive prey of moulting shelducks, probably due to the high densities of the species (Kraan et al. 2006). *C. volutator* also occurs in high abundance in the Elbe estuary, which is the core moulting area for shelducks in the Wadden Sea, but is less common in the North Frisian Wadden Sea area (FTZ, unpublished data). Interestingly, *C. volutator* was not found in the samples from the Elbe estuary or peripheral areas, even though 11 stomach contents and all the faecal samples originated from this area. Likewise, amphipods and *C. crangon* may be profitable prey, but are usually not available in high abundance within the shelduck's feeding habitat. Shelducks can be flexible in terms of their diet; e.g. in their wintering grounds in the Camargue, France, where their diet was found to consist of insects, mainly coleoptera and diptera, crustaceans (*Artemia* spp.), ostracods, algae, and seeds (Walmsley and Moser 1981).

Applicability of beached birds for diet analyses

Although analysing the stomach contents of beached birds was found to be unsuitable for dietary analysis of some pelagic species, such as black-legged kittiwakes and northern gannets (Markones and Guse 2009), beached individuals of several coastal bird species were found to be a useful source of dietary information (Schwemmer et al. 2012). Pelagic species are probably less suitable because of the longer time the carcasses spend floating on the sea surface before being found, meaning that the processes of digestion, degradation of calcareous prey, and decomposition may be too far advanced (Schwemmer et al. 2012). Variance analysis of the current data indicated the suitability of the stomach contents used in this study, but the state of decomposition may be an important factor.

It is possible that weakened or ill birds may change their feeding behaviour and become more opportunistic, as flights to more profitable feeding grounds become too energy consuming. For example, Markones and Guse (2009) found that the stomach contents of beached black-legged kittiwakes contained mainly the remains of coastal prey, suggesting that their movement and foraging abilities had been restricted before dying. It is therefore necessary to evaluate the suitability of beached birds for diet analysis in each case, and to combine the results with data from other sources, such as faeces, pellets, or regurgitations, if possible (Barrett et al. 2007).

The findings made in the current study provide important baseline data for food web models, but moreover the stomach and faeces analyses used in this study provide an efficient and low-cost tool for a top-down approach to monitor marine food webs. In accordance with studies elsewhere, our results showed an increase of neobiotic species at least in the diet of eiders (e.g. Tulp et al. 2010; Schwemmer et al. 2019; Laursen and Møller 2022). Population trends of both species in the study area are significantly declining (Kleefstra et al. 2022). Changes of food choice/availability over the last decades as found for common eiders in this study might be a key issue.

Occurrence of microplastics

We found a surprisingly high abundance of microplastic across both species and sample types considered. This suggests a high degree of contamination, both in the intertidal and subtidal habitats of the Wadden Sea. We hypothesized a different contamination of our study species with microplastics reflecting recent findings of higher occurrence of microplastics in the intertidal as compared to the subtidal area (Mendes et al. 2021; Markic et al. 2023), but no such difference was found. However, our results clearly showed significantly larger microplastics in shelducks (feeding in the intertidal) compared to eiders (using mainly the subtidal). This is in line with a study by Markic et al. (2023) who found significantly larger plastic particles in the intertidal than in the subtidal. Given the high proportion of mud in the Wadden Sea, an accumulation of (larger) fibres within the muddy intertidal, which was described before elsewhere (Mendes et al. 2021), might take place. Microplastic (and occasionally mesoplastic) contamination was recorded in several invertebrate species in the Wadden Sea of Schleswig–Holstein, including typical prey species of eiders and shelducks (Fischer 2019). It is, therefore, possible that most small microplastic particles (i.e. the largest quantity in the present study) originated through trophic transfer by feeding on contaminated prey, while larger microplastics or mesoplastics were more likely to be taken up from other sources. Trophic transfer has already been demonstrated at lower trophic levels, e.g. from *M. edulis* to *C. maenas* (Farrell and Nelson 2013), as well as in top predators, such as grey seals (*Halichoerus grypus*; Nelms et al. 2018). Other possible scenarios include the uptake of micro- and mesoplastics during feeding, such as their uptake from the sediment by shelducks that sieve the sediment through specialized lamellae in their bills, plastic debris attached to the outside of mollusc shells (see Seng et al. 2020 for a study on microplastics attached to surfaces of seagrass and macroalgae) or simply floating in the water, which may get caught in the feathers and later taken up during preening. As indicated by the large proportion of the comparably small mud snails, amphipods and Nereididae, shelducks usually take up small prey items while sieving the sediment. This contradicts our finding of significantly larger microplastic filaments found in the samples of this species and indicates that at least a certain proportion of the microplastics might have been taken up directly from the sediment as previous studies found larger microplastics in sediments of the intertidal than in the subtidal (Markic et al. 2023). Although plastic colour is known to influence the chance of being ingested by birds (see review of Provencher et al. 2017), we did not find any obvious differences in colour of filaments between the species (and sample types). Therefore, it seems unlikely that the study species had mistaken the filaments as potential food but rather ingested them by chance.

As plastic debris got analysed alongside diet remains, it is, therefore, likely that the quantity of plastic debris was underestimated, because the amount of shell fragments and other residues will have made it nearly impossible to find all plastic debris simply using a stereoscope. Although we performed an FTIR analyses with a subset of the small fibres, it was not possible to receive any definite results due to the small diameter of the fibres. Given that the spectra indicated that the filaments were likely polyamides with a protein coating, this strongly suggests that the filaments were likely digested or mixed with organic matter. A certain degree of contamination with airborne dust fibres (at least among the smallest size range < 1 mm) which is a known problem in studies of microplastics (Hermsen et al. 2017; Kühn et al. 2020) could, however, not get ruled out, as well as mistaking natural structures for microplastics. Thus, it remains unclear if particularly the smaller filaments found were indeed microplastics. However, given that we found significantly larger filaments in the shelduck samples as compared to the eider samples, which would not have been the case if the samples were just contaminated by airborne fibres, it can be assumed that at least a high proportion of the filaments were ingested by the birds. Finally, given that numerous studies have found microplastics in sediment and water from the Wadden Sea and in potential prey organisms, often in high quantities (e.g. Dekiff et al. 2014; Devriese et al. 2015; Fischer 2019; Leslie et al. 2013; Liebezeit and Dubaish 2012; Van Cauwenberghe, et al. 2015), it seems unlikely that all the plastic debris found in the samples originated from contamination or mistaken identification. Furthermore, plastic filaments in the samples were often firmly attached to the residues of prey organisms or plant material. Previous studies investigating plastic debris in waterbirds and seabirds also found microplastics in faeces, as in northern fulmars (*Fulmarus glacialis*; Provencher et al. 2018), mallards (*Anas platyrhynchos*), and shelducks (Gil-Delgado et al. 2017).

It can only be speculated about the origin of microplastics among prey remains of both seabird species. However, given that the vast majority of the plastic debris occurred as filaments and given their bright colours, it is very likely that remains of plastic fishing gear is a potential source (Montarsolo et al. 2018).

The current study found uptake and excretion of plastic debris by both eiders and shelducks, with comparably high levels of contamination in both species, and a lower level of contamination in faeces compared with stomach contents. The fact that many of the birds' stomachs were nearly empty but still contained microplastics indicates some retention. The direct effects of the high level of microplastics on the two study species are currently unknown. In contrast to species taking up large quantities of meso- and macroplastics, such as the fulmar (van Franeker et al. 2011), shelducks and eiders are not likely to starve to death as a consequence of a severe plastic load. However, given that microplastics have also been shown to enter the bloodstream from the gut (Browne et al. 2008) and to absorb and transfer other contaminants (Teuten et al. 2009), consequences for eiders and shelducks cannot be ruled out.

Conclusion

Both eiders and shelducks were found to consume a diversity of prey species; however, eiders focused mainly on *C. edule*, while shelducks mainly fed on *C. edule* and *P. ulvae*. Eiders and shelducks may thus have significant impacts on these focus prey species in the subtidal and intertidal zones, respectively. Their diet choice may also indicate changes in the local biocoenosis of macrozoobenthos, such as the current increase in *M. edulis* reflected by the eiders' diet. The current study provides up-to-date information on the diet choices of two numerous benthivorous seabird species in the intertidal and subtidal zones of the south-eastern Wadden Sea which is an important basis for food web models. Furthermore, the diet choice of both species provides an optimal monitoring tool to detect climate-driven or anthropogenically induced changes in marine food webs such as the occurrence of neobiotic species (e.g. Tulp et al. 2010; Schwemmer et al. 2019; Laursen and Møller 2022) in order to inform nature conservation. Finally, the strong population declines of both species (Kleefstra et al. 2022) are additional indicators to illustrate the ongoing changes in the marine food web.

The current study quantified the presence of plastic debris in stomach and faeces samples from both species and proved a high degree of microplastic contamination both in the intertidal and subtidal habitat. Although the issue of trophic transfer of microplastics in birds needs to be investigated further, the high quantities of plastic filaments in the samples suggest that the birds obtained the plastic particles either by indirect ingestion (via contact with the sediment) or through trophic transfer. Given that previous studies found similar microplastic contamination in the invertebrate prey species of shelducks and eiders, the latter option cannot be ruled out. The high rate of microplastic intake by the two study species in combination with their significant population declines (Kleefstra et al. 2022) illustrate the need to assess potential direct effect on the health status of the birds.

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Author contributions Conceptualization: PS; methodology: PS, SG; analyses: AB, AB, PS; writing—original draft preparation: AB, PS; writing—review and editing: AB, PS, AB, SG; supervision: PS.

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Declarations

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