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Albatrosses and petrels at South Georgia as sentinels of marine debris input from vessels in the southwest Atlantic Ocean

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ABSTRACT

Increasing amounts of anthropogenic debris enter the ocean because of mismanagement in coastal communities and, despite a global ban on deliberate dumping, also from vessels, endangering wildlife. Assessing marine plastic pollution directly is challenging, and an alternative is to use seabirds as bioindicators. Our analyses of long time-series (26-years) revealed substantial variation in the amount, characteristics and origin of marine debris (mainly macroplastics and mesoplastics, and excluding fishing gear) associated with seabirds at South Georgia, and, for two species, long-term increases in incidence since 1994. Annual debris recovery rates (items per capita) were 14 × higher in wandering albatrosses *Diomedea exulans*, and 6 × higher in grey-headed albatrosses *Thalassarche chrysostoma* and giant petrels *Macronectes* spp., than in black-browed albatrosses *T. melanophris*, partly related to differences in egestion (regurgitation), which clears items from the proventriculus. Although some debris types were common in all species, wandering albatrosses and giant petrels ingested higher proportions that were food-related or generic wrapping, gloves, clear or mixed colour, and packaged in South America. This was highly likely to originate from vessels, including the large South American fishing fleets with which they overlap. Debris associated with the two smaller albatrosses was more commonly shorter, rigid (miscellaneous plastic and bottle/tube caps), and packaged in East Asia. Grey-headed albatrosses are exposed to large and increasing amounts of user plastics transported from coastal South America in the Subantarctic Current, or discarded from vessels and circulating in the South Atlantic Gyre, whereas the lower debris ingestion by black-browed albatrosses suggests that plastic pollution in Antarctic waters remains relatively low. Current plastic loads in our study species seem unlikely to have an impact at the population level, but the results nevertheless affirm that marine plastics are a major, trans-boundary animal-welfare and environmental issue that needs to be addressed by much-improved waste-management practices and compliance-monitoring both on land and on vessels in the south Atlantic.

1. Introduction

There has been a rapid increase in global plastics production in recent decades, with no signs of a downturn (Geyer et al., 2017), and also in the volume entering the oceans (Jambeck et al., 2015). The latter is a huge problem in coastal environments and also in the open ocean, as buoyant plastics are transported long distances in currents, accumulating in gyres and other convergence regions (Law et al., 2010; Wichmann et al., 2019). Many marine animals ingest floating plastics that are either mistaken for natural food, are attached to targeted items such as fish eggs, or are acquired secondarily in the stomachs of their prey (Fry et al., 1987; Ryan, 1988). Mortality of turtles, cetaceans, seals and seabirds resulting from ingestion or entanglement in plastics is common, and although few studies have provided incontrovertible evidence of impacts at the population level, plastics are increasingly perceived as a major global threat to marine ecosystems (Gall and Thompson, 2015).

The majority of plastics in the ocean originates on land, and public outcry over effects on communities, habitats and wildlife has challenged regulators, manufacturers and consumers to reduce production and reliance on plastics in a variety of ways (Moore, 2008). Attention has also focused on the fishing industry to minimise deliberate discarding and accidental loss of gear, which causes subsequent problems associated with ghost-fishing, entanglement and ingestion (Phillips et al., 2010; Ryan, 2018; Votier et al., 2011). However, many other non-organic items (particularly packaging materials) are lost or deliberately dumped overboard; although these can originate from vessels of many types, there is growing evidence that the fishing industry is responsible

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for a substantial proportion of anthropogenic debris (both fishing and consumer items) recorded at sea and on beaches (Ryan et al., 2019; Unger and Harrison, 2016). This is despite the global ban on deliberate dumping at sea of all waste except food, identified cargo residues, animal carcasses, identified cleaning agents and additives, and non-harmful cargo residues in washwater, under the 1978 Protocol to the International Convention for the Prevention of Pollution from Ships (MARPOL), and subsequent international and national legislation (Chen and Liu, 2013; Lentz, 1987).

Seabirds are amongst the marine vertebrates with the highest known ingestion rates of plastics and other marine debris (Gall and Thompson, 2015). This applies particularly to the order Procellariiformes (albatrosses and petrels), especially the smaller petrels because of their narrow, angled pyloric sphincter, which traps indigestible material in the ventriculus (or gizzard) (Furness, 1985). A recent study suggested that burrowing petrels were more likely to confuse floating plastics - which acquire a dimethyl sulfide (DMS) signature from biofouling – with natural prey because of smell, rather than appearance (Savoca et al., 2016). However, an alternative view is that DMS produced by marine phytoplankton is an olfactory cue mainly at large scales - attracting seabirds to prey patches at frontal systems, eddies, and upwellings (Morét-Ferguson et al., 2010). Although plastics and zooplankton co-occur at high densities in these regions, other factors affecting exposure and retention (diet, at-sea distribution, diving depth, tendency to regurgitate, etc.) are probably the predominant drivers of the substantial variation in plastic loads among seabird species, and age classes (Dell'Ariccia et al., 2017; Ryan et al., 2016).

Assessing distribution and levels of marine plastic pollution directly from ship-based surveys is expensive and logistically challenging, and requires complex models that incorporate wind-driven vertical mixing and the trajectories of ocean currents (Jambeck et al., 2015; Law et al., 2010). An alternative that may better represent exposure to marine predators in general, is to use seabirds as bioindicators, benefiting from their natural tendency to accumulate indigestible items in the gut, tractability for sampling, and the availability of dead birds on beaches (Ryan et al., 2009; Van Franeker et al., 2011; Van Franeker and Law, 2015). Their effectiveness as biomonitors is exemplified by documented reductions in incidence of industrial plastic pellets (nurdles) in their stomach contents since the early 1990s, consistent with efforts by the plastic industry to prevent pellet release (Ryan et al., 2009; Van Franeker et al., 2011). Seabirds also offer the advantages of being charismatic megafauna in whose welfare the public are interested; albatrosses and penguins in particular are icons of the marine environment and many are threatened (Dias et al., 2019; Phillips et al., 2016).

Despite their potential as sentinel species for highlighting the dramatic increase in volume of user plastics entering the oceans – and thereby encouraging industries and consumers to respond - there are few studies of variation in ingestion rates of seabirds that extend into the last 1–2 decades (Provencher et al., 2010; Van Franeker and Law, 2015). Here, we analyse some of the longest time-series available; those from albatrosses Diomedeidae and giant petrels *Macronectes* spp. breeding at South Georgia, southwest Atlantic Ocean. Our aims were to: (i) relate differences in the amount of marine debris (excluding fishing gear) recovered from each species to their ecology and distribution, (ii) examine annual variation in debris ingestion and the contributing factors, (iii) characterise the type, size, colour and country of origin of debris to better identify proximate sources (either from the land due to inadequate waste management by coastal communities, or lost or dumped directly at sea from vessels), and (iv) examine other reasons (e.g. related to debris colour), why birds might preferentially ingest particular items. Results are discussed in the context of monitoring the increasing plastic pollution of the oceans, possible impacts on seabirds, and options for improving waste management, in particular, improving compliance of fishing and other vessels with the MARPOL convention.

2. Material and methods

Monitoring of fishing gear and marine debris, including plastics, associated with seabirds breeding at Bird Island, South Georgia (54°00′S, 38°03′W) was initiated in austral summer 1993/94, and has since been carried out annually using consistent methodology (Huin and Croxall, 1996; Phillips et al., 2010). This involves daily to weekly visits to wandering albatrosses *Diomedea exulans*, black-browed albatrosses *Thalassarche melanophris*, grey-headed albatrosses *T. chrysostoma*, northern giant petrels *Macronectes halli* and southern giant petrels *M. giganteus* in demarcated study areas to record all fishing gear and other anthropogenic debris.

Differences in the incidence of fishing gear (hooks, line and floats) among species, and changes over time in relation to fishing effort and practices, were analysed previously (Phillips et al., 2010), and will not be considered further here. The majority of the non-fishing items, i.e., plastics and other marine debris, is found on the ground or in nests, often originating in pellets (boluses) of undigested material regurgitated spontaneously by adults or by chicks shortly before fledging, and in stomach contents of chicks obtained by induced regurgitation for targeted diet studies (see below). A few items of debris in spontaneous regurgitations during routine ringing were excluded because these were rare events and varied in number each year.

The survey areas are visited at intervals of days to weeks, specified in standard field protocols, in each breeding season, and the areas, work routine and therefore search effort are consistent in successive years (Phillips et al., 2010). Since the debris monitoring started, population sizes of all albatrosses have decreased (Poncet et al., 2006; Poncet et al., 2017), and of northern and southern giant petrels have, respectively, increased slowly or remained stable (Gianuca et al., 2019). Total numbers of nests of each species counted during incubation in the study areas are therefore indicative of sample sizes each year. The number of items found, divided by the number of nests, provides a per capita index for comparing debris recovery rates. Pearson correlations were used to test for linear trends over time for each taxon.

The incidence of marine debris was also recorded in stomach contents obtained by induced regurgitation of chicks targeted for diet studies (for details and effects, see Phillips, 2006). Sampling took place annually from 1996 to 2019 for grey-headed and black-browed albatrosses, only in 2008 and 2009 for the wandering albatross, and 2015 to 2017 for giant petrels. Given the significant overall increase over time in recovery rates of marine debris found on the ground for grey-headed and black-browed albatrosses, debris loads (total items/stomach samples obtained) were compared among species based only on samples collected since 2008. However, debris items obtained in previous years from grey-headed and black-browed albatrosses were included in other analyses.

Each debris item was assigned to a species, species-pair (giant petrels, which nest in similar areas), or unknown species, depending on origin (stomach contents; characteristic pellet type; specific subcolony or study area). Items were categorised as "Gloves", "Net/string/rope", "Bottle/tube cap", "Food/drink wrapper", "Plastic bag/wrapping" (i.e. without food-related branding), "Polystyrene/foam", "Misc. plastic" (including a few small pellets which may have been industrial plastics), "Misc. rubber", or "Other non-fishing" (including glass, wood, wax, cloth, paper). Rigid and non-rigid (flexible) items were distinguished, and the longest dimension (hereafter "maximum length") measured with a ruler to the nearest mm. Country or region where the item was packaged was determined where possible from branding (text and logos). Item colour was categorised into dark (black or green), light (clear and all other colours), or mixed, broadly following Santos et al. (2016). The relative frequencies of different types, countries of origin, and colours of debris were compared using chi-square tests, with some categories or species pooled or excluded, as appropriate, to ensure that no more than 20% of expected counts were fewer than 5. Lengths of rigid and flexible items were compared among taxa using Levene's test

Table 1
Number of items, sample size (breeding pairs in study areas) and recovery rates (items per breeding pair, x 1000) of marine debris (excluding fishing gear) found on the ground in study areas of albatrosses and giant petrels at Bird Island, South Georgia, 1994 to 2019.

Year	Wandering albatross			Grey-headed albatross			Giant petrels			Black-browed albatross		
	Items	Pairs	Rate	Items	Pairs	Rate	Items	Pairs	Rate	Items	Pairs	Rate
1994	11	1348	8.2	6	3397	1.8	2	350	5.7	0	4192	0.0
1995	2	1387	1.4	3	4665	0.6	0	356	0.0	0	1700	0.0
1996	5	1243	4.0	3	5029	0.6	1	361	2.8	0	3650	0.0
1997	0	1307	0.0	1	1923	0.5	0	367	0.0	0	3782	0.0
1998	22	1235	17.8	10	3859	2.6	5	372	13.4	7	3779	1.9
1999	20	1182	16.9	15	4629	3.2	4	378	10.6	3	3259	0.9
2000	40	1142	35.0	29	2387	12.1	2	383	5.2	7	3531	2.0
2001	32	1060	30.2	37	3398	10.9	0	307	0.0	10	3963	2.5
2002	62	1066	58.2	56	3426	16.3	1	384	2.6	4	3567	1.1
2003	54	992	54.4	30	3062	9.8	5	271	18.5	5	3839	1.3
2004	14	948	14.8	26	3219	8.1	12	429	28.0	9	3192	2.8
2005	14	927	15.1	7	2667	2.6	7	432	16.2	2	3091	0.6
2006	18	851	21.2	9	2750	3.3	7	409	17.1	2	2981	0.7
2007	38	802	47.4	12	2590	4.6	5	448	11.2	3	2967	1.0
2008	7	861	8.1	3	2685	1.1	1	516	1.9	1	3216	0.3
2009	16	865	18.5	19	2589	7.3	19	553	34.4	6	3078	1.9
2010	28	779	35.9	31	2298	13.5	2	528	3.8	5	3059	1.6
2011	25	844	29.6	67	1970	34.0	3	436	6.9	16	2842	5.6
2012	14	809	17.3	20	2348	8.5	1	455	2.2	3	2803	1.1
2013	6	773	7.8	13	1702	7.6	2	453	4.4	8	2597	3.1
2014	1	877	1.1	25	1952	12.8	0	469	0.0	11	2481	4.4
2015	28	772	36.3	17	2248	7.6	5	482	10.4	1	2714	0.4
2016	14	800	17.5	33	1456	22.7	9	459	19.6	3	2700	1.1
2017	38	688	55.2	25	1438	17.4	3	403	7.4	5	2412	2.1
2018	16	661	24.2	21	1593	13.2	1	420	2.4	6	2393	2.5
2019	16	644	24.8	30	1523	19.7	3	470	6.4	7	2378	2.9
Total	**541**			**548**			**100**			**124**		
Mean	**20.8**	**956**	**23.1**	**21.1**	**2723**	**9.3**	**3.8**	**419**	**8.9**	**4.8**	**3083**	**1.6**
Rel. rate			**14.32**			**5.78**			**5.50**			**1**

for homogeneity of variances followed by Kruskal-Wallis tests. The debris monitoring was set up originally for reporting to the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and, for consistency, “year” in the results corresponds to each period from 1 April to 31 March, e.g., 1994 refers to the period from 1 April 1993 to 31 March 1994.

3. Results

3.1. Marine debris found in study areas; comparisons among species and years

The number of items of marine debris found in study areas of wandering albatross, grey-headed albatross, black-browed albatross and giant petrels during routine monitoring at Bird Island each year ranged, respectively, from 0 to 62 (mean of 20.8; total 541), 1 to 67 (mean of 21.1, total 548), 0 to 16 (mean of 4.8, total 124) and 0 to 19 (mean of 3.8, total 100) [grand total 1313] during the 26-year study from 1994 to 2019 (Table 1). Peaks in timing of recovery depended on the species: mainly November to January (79% of items recovered; chicks around fledging, and adults in incubation) for wandering albatrosses; September/October to December (51–62% of items recovered; adults in incubation), and March/April to May/June (15–39% of items recovered; mainly chicks around fledging) for the other albatrosses and giant petrels. There were no significant correlations between number of recorded debris items and year for any albatross species or the giant petrels (r_{24} = 0.013 to 0.346, P = 0.084 to 0.951). However, there were significant increases with year in debris recovery rates per capita for both grey-headed and black-browed albatrosses (r_{24} = 0.596, P = 0.001 and r_{24} = 0.486, P = 0.012, respectively), but not the wandering albatross (r_{24} = 0.241, P = 0.236) or giant petrels (r_{24} = 0.078, P = 0.706) (Fig. 1). Pooling the data for all years, debris recovery rates per capita were 14 × higher in the wandering albatross, and 6 × higher in the grey-headed albatross and giant petrels, than in the black-browed albatross (Table 1).

3.2. Debris ingestion based on stomach contents (chick diet samples)

Pooling the data since 2008, relative marine debris loads decreased in order as follows: grey-headed albatross (29 in 351 samples = 0.083); wandering albatross (3 in 70 samples = 0.043); giant petrels (3 in 154 samples = 0.019); black-browed albatross (5 in 347 samples = 0.014) (Table 2). Debris loads in stomach contents were therefore 5.7 × higher in the grey-headed albatross, 3.0 times higher in the wandering albatross, and 1.4 × higher in giant petrels than in the black-browed albatross.

3.3. Variation among species in type, size, country of origin and colour of marine debris

There were significant differences among the four taxa in the frequencies of different types of debris (χ^2_{18} = 629.4, P < 0.001; pooling the counts of miscellaneous rubber, polystyrene/foam and other items into a single category; Table 3). Considering categories that included more than 5% of items for any taxon, most items ingested by the wandering albatross and giant petrels were plastic bags/wrapping (44.9% and 27.6%), food/drink wrapping (23.0% and 19.0%), miscellaneous plastic (16.6% and 31.4%), and gloves (5.3% and 8.6%), whereas most ingested by grey-headed and black-browed albatrosses were miscellaneous plastics (61.9% and 62.1%), bottle/tube caps (25.3% and 17.4%) and, to a lesser extent, plastic bags/wrapping (5.2% and 9.1%).

Comparison of debris lengths among taxa were carried out separately for rigid (bottle/tube caps and miscellaneous plastics) and flexible items (all other categories). For both rigid and flexible items, variance in lengths were heterogeneous (Levene's test, $W_{3,577}$ = 13.0,

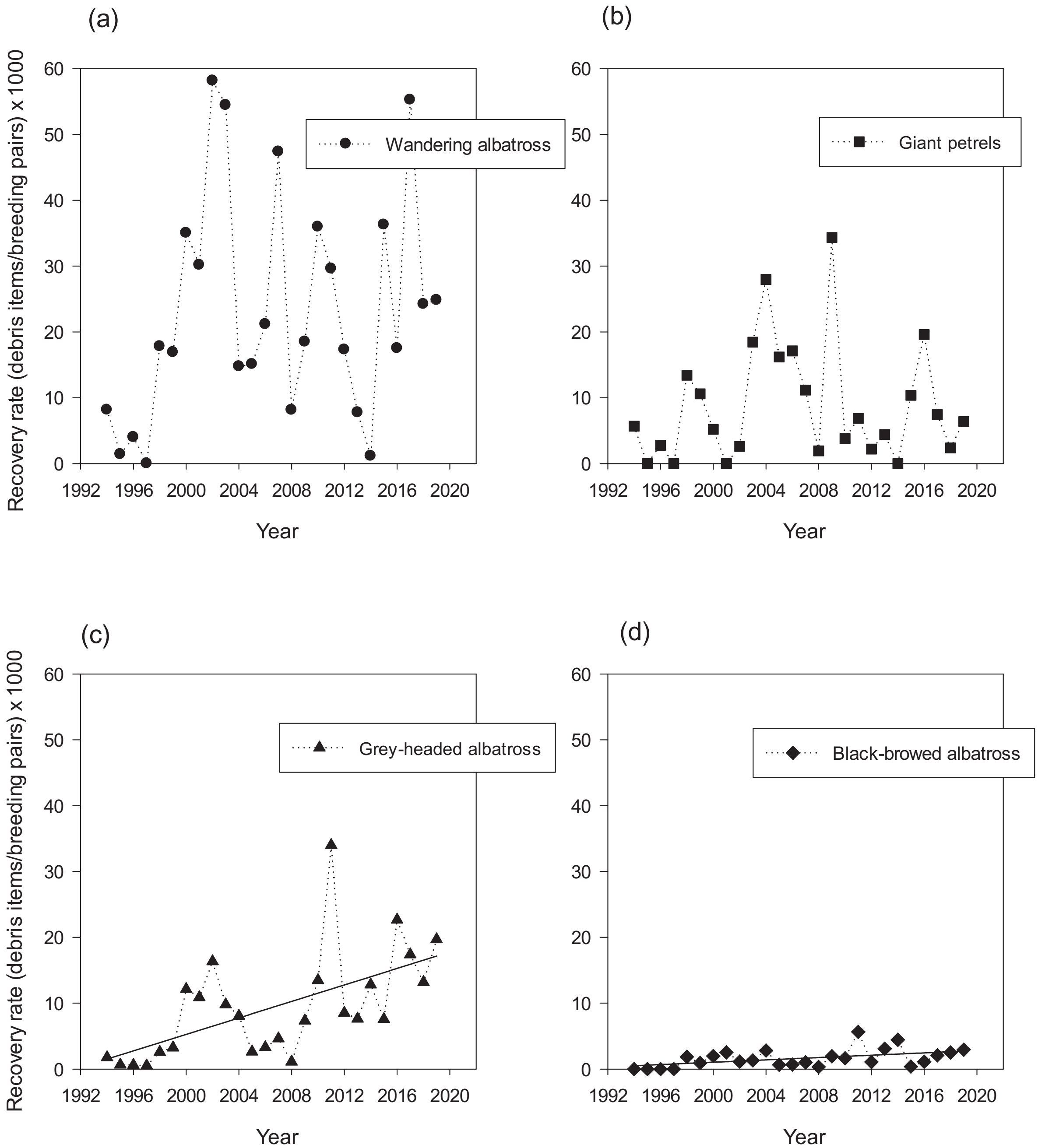

Fig. 1. Changes in recovery rates (items per breeding pair, × 1000) over time of marine debris (excluding fishing gear) found on the ground in study areas of albatrosses and giant petrels at Bird Island, South Georgia, 1994 to 2019, (a) wandering albatross, (b) giant petrels, (c) grey-headed albatross and (d) black-browed albatross. Regression lines included where correlations with year were significant (see Results).

$P < 0.001$ and $W_{3,455} = 4.34$, $P = 0.005$, respectively), and median lengths differed among taxa (Kruskal-Wallis H = 18.8, $P < 0.001$ and H = 39.4, $P < 0.001$, respectively). Median lengths of rigid items were similar in wandering, grey-headed and black-browed albatrosses (median and interquartile range [IQR] of 29 mm [IQR 17 to 60], 30 mm [IQR 20 to 40] and 28.5 mm [IQR 20 to 39], respectively), and shorter in giant petrels (18 mm, IQR 10 to 28.75). Median lengths of flexible items were similar (and longest) in the wandering albatross and giant petrels (median and IQR of 150 mm [IQR 85 to 272.5] and 150 mm [IQR 80 to 250], respectively), intermediate in the black-browed albatross (80 mm, IQR 52 to 225), and shortest in the grey-headed albatross (65 mm, IQR 30 to 116) (Fig. 2).

Countries of origin (packaging) were identified for 88 items of marine debris, which was mostly food/drink wrapping (68 items; 77%), or bottle/tube caps (11 items; 13%, including drink-related), but also included plastic bags/wrapping (5 items; 6%) and miscellaneous plastic (4 items; 5%). These were in South America, East Asia, Europe, or the USA (Fig. 3, Supplementary Table 1). Excluding the black-browed albatross, and pooling data for the wandering albatross and giant petrels (as the debris was otherwise quite similar) because of the small samples, a higher proportion of the marine debris of known origin ingested by the wandering albatross and giant petrels was from South America, and by the grey-headed albatross was from East Asia ($\chi^2_{27} = 10.3$, $P = 0.06$).

There were highly significant differences among the four taxa in the frequencies of different colours of debris ($\chi^2_{27} = 378.7$, $P < 0.001$; pooling the less common colours of black, yellow, grey and purple into a single category; Table 4). The most common colours of debris ingested

Table 2
Number of items of marine debris (excluding fishing gear) recorded in stomach contents of albatross and giant petrel chicks sampled for diet studies at Bird Island, South Georgia, 2008 to 2019.

Year	Grey-headed albatross		Wandering albatross		Giant petrels		Black-browed albatross	
	Items	Samples	Items	Samples	Items	Samples	Items	Samples
2008	4	31	1	35				27
2009	3	30	2	35				30
2010	5	30					1	30
2011	3	20					1	20
2012		30						30
2013		30						30
2014	1	30					1	30
2015	6	30			1	42		30
2016		30			1	52	1	30
2017	4	30			1	60	1	30
2018	1	30						30
2019	2	30						30
Total	**29**	**351**	**3**	**70**	**3**	**154**	**5**	**347**

by both the wandering albatross and giant petrels were clear, white, mixed and blue, whereas those ingested by both grey-headed and black-browed albatrosses were red, orange, blue or white.

4. Discussion

4.1. Methodological considerations

This study found substantial variation in the amount, type, country of origin and colour of plastics and other marine debris associated with albatrosses and giant petrels at South Georgia, and, for grey-headed and black-browed albatrosses, long-term increases in incidence. It is important to note that the data presented here exclude items of fishing gear (cf. Phillips et al., 2010), and that the sampling was largely of macroplastics (> 25 mm) and mesoplastics (5–25 mm). Unlike in smaller petrels, the great majority of items ingested by our study species were larger than the most common type of marine debris found at the ocean surface, which is < 10 mm in size (Morét-Ferguson et al., 2010; Roman et al., 2019c). Microplastics (1–5 mm) could have been missed, but being much smaller than natural prey may in any case be ignored by albatrosses and large petrels feeding at sea. Even if microplastics were ingested secondarily in stomach contents or tissues of prey, they are subsequently likely to be eroded by physical processes in the gut or may pass into the small intestine and be excreted (Roman et al., 2019c).

The great majority of debris was user plastics; pellets that could have been industrial resin (nurdles) were very rare. This is typical of studies of other large, surface-feeding albatrosses and petrels in the last 1–2 decades, (Barbieri, 2009; Carey, 2011; Petry and Benemann, 2017; Vlietstra and Parga, 2002). It also accords with the few long-term time-series, which show decreases in abundance of nurdles on beaches, at sea and in seabird stomachs, consistent with improved efforts since the early 1990s by the plastic industry to prevent their release (Law et al., 2010; Ryan et al., 2009; Van Franeker et al., 2011; Van Franeker and Law, 2015).

Most studies assessing debris in stomach contents involve dissection of seabirds found dead at colonies or on beaches, or bycaught in fisheries (Ryan et al., 2016; Van Franeker and Law, 2015). These approaches simplify quantification of frequency of occurrence compared with recording items on the ground, but advantages of the latter are that it is non-invasive, low cost, more predictable (search effort can be standardised across years) and more convenient (carcasses or diet samples do not need to be stored). In addition, birds found dead could have starved because of high plastic loads and be unrepresentative of the wider population (Rodríguez et al., 2018). It is a moot point as to which approach better accounts for the ability of many seabirds to regurgitate indigestible material as pellets or when provisioning offspring; both processes clear items from the proventriculus and explain why plastic loads decrease in adults over the breeding season (Ryan, 1988).

4.2. Inter-specific differences in marine debris incidence, types and sources

Pooling debris from the two sampling methods, there were clear differences in the incidence and characteristics of items associated with each study species. Average recovery rates for debris on the ground per capita were 14 × higher in the wandering albatross, and 6 × higher in the grey-headed albatross and giant petrels, than in the black-browed albatross. The incidence of debris in chick diet samples was

Table 3
Categories of marine debris (excluding fishing gear) recorded on the ground and in chick diet samples of albatrosses and giant petrels at Bird Island, South Georgia, 1994 to 2019.

Category	Wandering albatross		Giant petrels		Grey-headed albatross		Black-browed albatross	
	Items	%	Items	%	Items	%	Items	%
Plastic bag/wrapping	254	44.9	29	27.6	31	5.2	12	9.1
Food/drink wrapping	130	23.0	20	19.0	12	2.0	4	3.0
Bottle/tube cap	24	4.2	5	4.8	151	25.3	23	17.4
Miscellaneous plastic	94	16.6	33	31.4	369	61.9	82	62.1
Gloves	30	5.3	9	8.6	3	0.5	3	2.3
Net/string/rope	9	1.6	4	3.8	5	0.8	5	3.8
Miscellaneous rubber	6	1.1			7	1.2	1	0.8
Polystyrene/foam	5	0.9	3	2.9	7	1.2	2	1.5
Other	14	2.5	2	1.9	11	1.8		
Total	**566**		**105**		**596**		**132**	

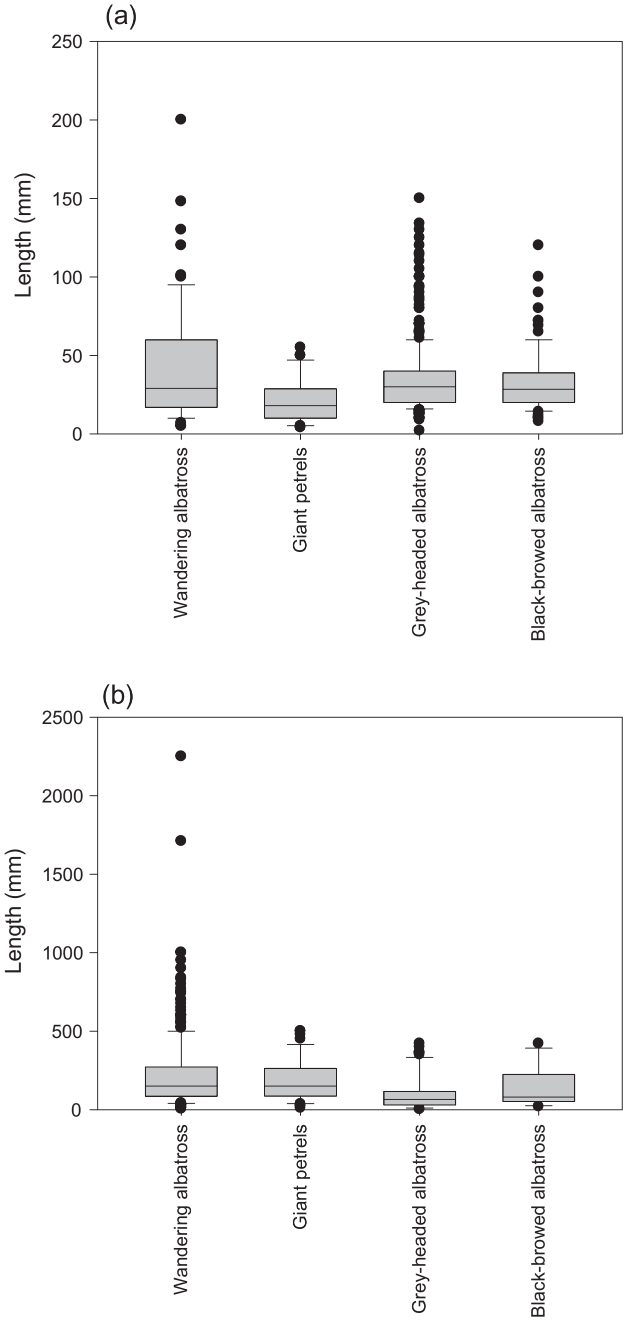

Fig. 2. Box plots of lengths of marine debris (excluding fishing gear) found on the ground or in chick diet samples of albatrosses and giant petrels at Bird Island, South Georgia, 1994 to 2019, (a) rigid items, and (b) non-rigid (flexible) items.

5.7 × higher in the grey-headed albatross, 3.0 × higher in the wandering albatross and 1.4 × higher in giant petrels than in the black-browed albatross. As in all approaches to monitoring plastics loads in seabirds, sampling provides snapshots that do not account for flux, i.e. the balance among ingestion, digestion and egestion rates over time. The chick diet samples will be more representative of typical plastic loads in the proventriculus, as giant petrels and, in particular, wandering albatrosses, produce more pellets than either grey-headed or black-browed albatrosses (based on ratios of pellets:breeding pairs in our study areas). Regardless, plastic loads in chick diet samples should not be compared directly with results from dissection of adult seabirds or chicks, unless these report separately on material in the proventriculus (c.f. most such studies, which typically describe the contents of the ventriculus, in which much smaller items of marine debris tend to accumulate: Roman et al., 2019c).

All our study species are wide-ranging, feeding both on natural prey close to the sea surface and, to variable extents, on discards from fisheries (Cherel et al., 1996; Favero et al., 2003; Otley et al., 2007). Although wandering albatrosses have by far the largest bills (mean length 167.3 mm: Cuthbert et al., 2003), those of black-browed and grey-headed albatrosses (mean lengths of 115.8 mm and 110.1 mm, respectively: Phillips et al., 2004) are longer than in giant petrels (mean of 95.4 mm: Hunter, 1984), and all but the very-longest, rigid debris item associated with a wandering albatross was within the range ingested by the other species (Fig. 2); hence gape size is not a factor affecting our results. Instead, by considering differences in at-sea distributions, and using the characteristics (type, size, colour, country of origin, etc.) of the debris as clues, it is possible to explain the differences in plastic loads, determine the main sources (fishing and other vessels *vs.* input from land), and identify pathways to improved waste management.

Although some types of debris were ingested in considerable amounts by every species, more items ingested by the wandering albatross and giant petrels were food-related wrapping, generic wrapping or gloves, were clear or mixed in colour, and had been packaged in South America. Given those characteristics and the propensity of these species to scavenge behind vessels, the debris was highly likely to have blown over-board or been deliberately discarded along with other waste, including from ship galleys (kitchens) or messes (eating areas). Long, pliable items such as packaging have a high surface to volume ratio and will become less buoyant within days or weeks of discarding because of the formation of biofilms, followed by accretion of fouling organisms (Barnes, 2002; Fazey and Ryan, 2016; Morét-Ferguson et al., 2010). They are therefore more likely to be ingested by a scavenging seabird within a short time of landing on the sea surface than later in the open ocean, particularly if clear and hence less noticeable in the water column.

Waters on the Patagonian Shelf and shelf-slope, and around the subtropical convergence are used intensively by wandering albatrosses during breeding (Clay et al., 2019; Froy et al., 2015), and the southern Patagonian Shelf also to some extent by both giant petrel species (Granroth-Wilding and Phillips, 2019). Hence the large South American fishing fleets (Clay et al., 2019) represent the major potential debris source. Indeed, 73% of diet samples obtained in the early 2000s from southern giant petrels in Patagonian colonies included anthropogenic items, many of which were thought to originate from fishing vessels (Copello et al., 2008). That the incidence of plastics is considerably lower in giant petrels from South Georgia (3 in 154 diet samples) is presumably because both breeding populations spend the majority of time foraging in Antarctic waters (Granroth-Wilding and Phillips, 2019).

4.3. *Effects of colour on marine debris ingestion*

Higher proportions of the marine debris found in association with the two smaller albatrosses, and particularly the grey-headed albatross, were shorter in length, rigid (miscellaneous plastic and bottle/tube caps), red, orange or blue in colour, and packaged in East Asia. In terms of the colour, it was hypothesised based on Thayer's Law (counter-shading) that surface-feeding seabirds preferentially ingest light plastic items because they are easier to see against the darker depths (Santos et al., 2016). Light items were indeed much more common than dark colours (black or green) for all our study species, and many other seabirds (Carey, 2011; Lavers et al., 2018; Vlietstra and Parga, 2002). That grey-headed and black-browed albatrosses ingested fewer clear items than the wandering albatross and giant petrels, despite evidence that they consume jellyfish (Cnidaria), comb jellies (Ctenophora) and tunicates (Catry et al., 2004), suggests that detectability rather than colour-matching (i.e. confusion) of debris with typical prey is the most

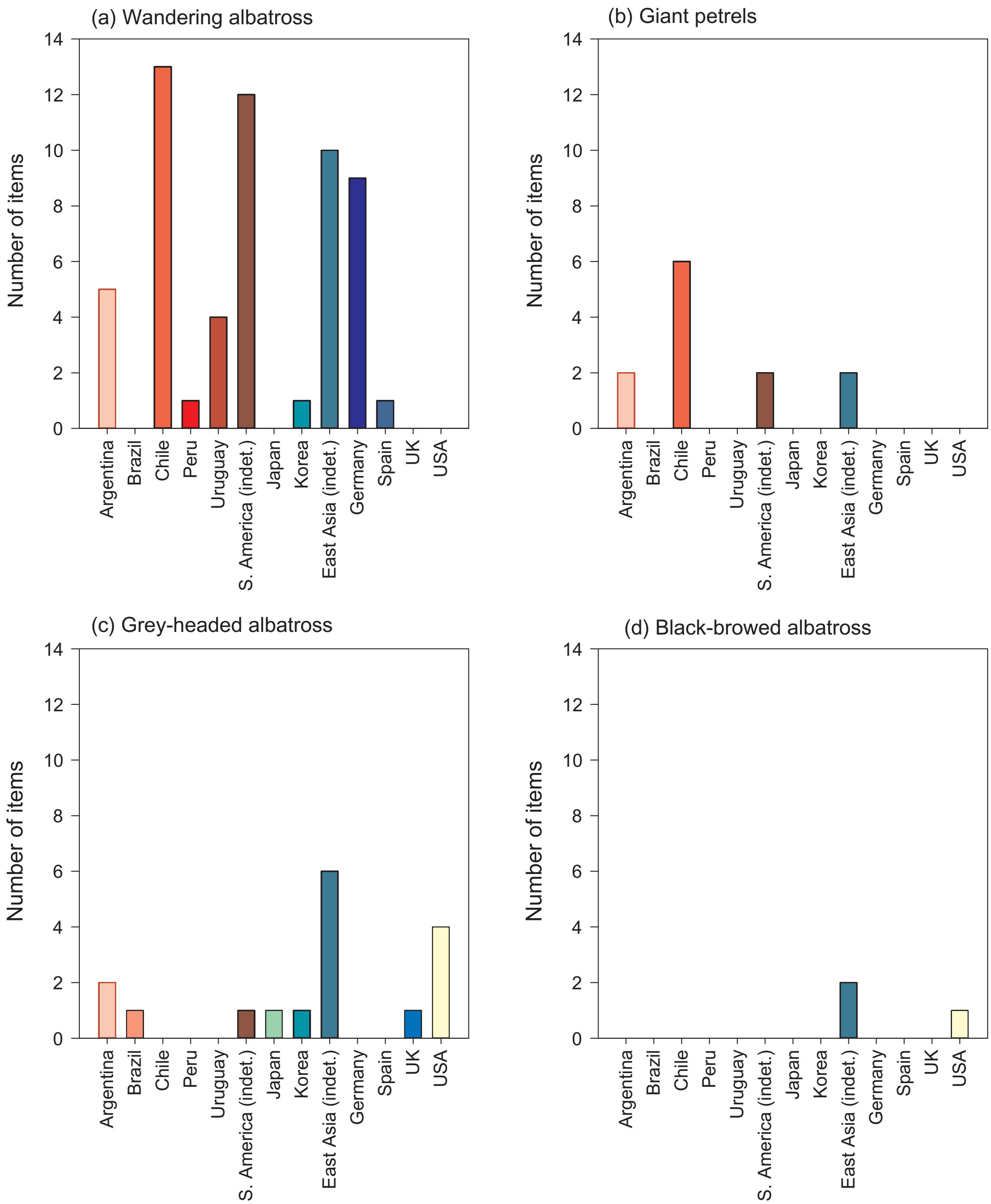

Fig. 3. Country or region of origin (packaging) of marine debris (excluding fishing gear) found on the ground or in chick diet samples of albatrosses and giant petrels at Bird Island, South Georgia, 1994 to 2019, (a) wandering albatross, (b) giant petrels, (c) grey-headed albatross and (d) black-browed albatross.

parsimonious explanation for the observed patterns. However, to entirely rule out selectivity, i.e. active preferences for particular colours, would be difficult without information on relative availability in the pelagic environment.

4.4. Exposure to marine debris in subantarctic and Antarctic waters

During breeding, and particularly in chick-rearing, grey-headed albatrosses feed predominantly around the Antarctic Polar Front (APF) or farther south (Phillips et al., 2004; Xavier et al., 2003). Black-browed albatrosses also feed to some extent around the APF, but mostly over the South Georgia shelf and shelf-slope, including near Shag Rocks, and farther south in the Scotia Sea (Wakefield et al., 2011). Given the characteristics and much lower quantities of debris associated with the black-browed albatross, the clear inference is that grey-headed albatrosses are exposed to large amounts of user plastics transported east from coastal South America in the Subantarctic Current, or discarded from vessels and circulating in the South Atlantic Gyre. The northern margin of their distribution comes close to the southern boundary of this gyre, where predicted densities of floating plastics are higher than in Antarctic waters (Eriksen et al., 2014). The greater incidence of debris from East Asia ingested by the grey-headed albatross therefore corroborates a recent study at Inaccessible Island which concluded that ships, particularly from East Asia, were responsible for most of the

Table 4
Colour of marine debris (excluding fishing gear) recorded on the ground and in chick diet samples of albatrosses and giant petrels at Bird Island, South Georgia, 1994 to 2019.

Colour	Wandering albatross		Giant petrels		Grey-headed albatross		Black-browed albatross	
	Items	%	Items	%	Items	%	Items	%
Light								
Clear	137	34.7	19	21.6	13	2.7	4	3.8
White	67	17.0	16	18.2	52	10.8	10	9.6
Blue	42	10.6	7	8.0	64	13.3	23	22.1
Red	24	6.1	7	8.0	185	38.4	37	35.6
Orange	14	3.5	7	8.0	75	15.6	15	14.4
Brown	10	2.5	2	2.3	20	4.1	4	3.8
Pink	12	3.0	5	5.7	33	6.8	5	4.8
Yellow	10	2.5	6	6.8	2	0.4		
Grey	10	2.5	2	2.3	4	0.8		
Purple	1	0.3			6	1.2	1	1.0
Mixed	46	11.6	12	13.6	14	2.9		
Dark								
Black	12	3.0	1	1.1	4	0.8		
Green	10	2.5	4	4.5	10	2.1	5	4.8
Total	**395**		**88**		**482**		**104**	

bottles – and, by inference, much of the other marine debris - floating in the central South Atlantic Ocean (Ryan et al., 2019).

In contrast, the limited amounts of debris ingested by black-browed albatrosses suggest that plastic pollution south of the APF (i.e. in Antarctic waters) remains relatively low. Although no licensed longline fishing vessels would have operated in summer south of the APF since the introduction of a closed fishing season at South Georgia in 1997, the waters are used by cruise ships, a small fishery targeting mackerel icefish *Champsocephalus gunnari*, and some other vessels. Adherence in this region to the MARPOL convention may be better than elsewhere, but even if not, there are far fewer vessels than in waters to the north, and the APF acts as a barrier to floating plastics entering the region.

There were no detectable long-term trends in the amount of debris associated with wandering albatrosses or giant petrels, perhaps because the majority of debris they ingest originates from vessels (which would mask trends for items floating in currents), and total demersal and pelagic fishing effort overlapping with wandering albatrosses has changed little since the early 1990s (Clay et al., 2019). In contrast, we found a long-term increase from the early 1990s in marine debris associated with both black-browed and grey-headed albatrosses. This matches with the predominant (but not universal) pattern in recent decades of decreases in industrial, and increases in number or mass of user plastics ingested by seabirds, particularly, but not exclusively, those that are surface-feeding, and including species in the South Atlantic (Jambeck et al., 2015; Lavers et al., 2018; Petry and Benemann, 2017; Provencher et al., 2010; Van Franeker et al., 2011).

4.5. Impacts of marine debris ingestion

Marine debris is recorded, often in high numbers, in stomach samples of many individuals of numerous seabird species, and some clearly die as a direct consequence; however, documented impacts of plastic ingestion at the population level are rare (Roman et al., 2019a). Images of Laysan albatross *Phoebastria immutabilis* and black-footed albatross *P. nigripes* chick carcasses filled with lighters, bottle caps, etc. are now emblematic of the pervasive presence of plastics in the oceans. Although Laysan but not black-footed albatross chicks with large volumes of plastics in the proventriculus weighed less - presumably from partial gut obstruction, blockage of enzyme secretion or appetite suppression – their survival to fledging was unaffected (Auman et al., 1998; Sievert and Sileo, 1993). Furthermore, global populations of both these species are currently stable or increasing (Phillips et al., 2016).

Inclusion of toxic substances in plastics, or contamination during manufacture or from adsorption of pollutants in the oceans may increase the health risk associated with ingestion (Colabuono et al., 2010; Mato et al., 2001; Turner, 2016). However, total intake from the diet will be much greater for the majority of pollutants, although not all (Tanaka et al., 2019). Some studies - but far from all that tested for such links - have found relationships between number or mass of ingested plastic and body condition or fat scores in unbiased samples (i.e. excluding beached birds) (Codina-García et al., 2013; Rodríguez et al., 2012; Roman et al., 2019b). Experimental feeding trials did not document effects of a large plastic load on assimilation efficiency (Ryan and Jackson, 1987), or, in another study, on mortality or reproduction, although there was evidence of partial endocrine disruption (Roman et al., 2019b). However, there can be sublethal effects of plastic ingestion on aspects of blood chemistry (Lavers et al., 2019), body mass and wing length of chicks (Lavers et al., 2014), and the more plastic ingested, the higher the risk of associated mortality (Roman et al., 2019a). Bearing the above in mind, although current plastic loads in the albatrosses and giant petrels at our study site seem not to have a serious impact unless a sharp item perforates the gut – as happened to a wandering albatross chick (Quinn *in litt.*) – marine plastics are nevertheless a major animal-welfare and environmental issue that needs to be addressed.

4.6. Recommendations for waste management

Although estimated densities of marine plastics in the Southern Ocean are relatively low (Eriksen et al., 2014), and our study species breed at South Georgia, 300 km south of the APF and 1350 km from the nearest town (Stanley, Falkland Islands; 2100 inhabitants), their extensive distributions expose them to marine debris discarded from vessels, or transported long distances in ocean currents. Our results therefore underline the pervasive, transboundary nature of the marine plastics problem. Globally, there are diverse solutions, particularly focusing on reducing, reusing and recycling on land (Moore, 2008). However, until these are properly implemented, huge quantities of mismanaged plastic waste generated annually by coastal communities - including in our study region by Brazil, Argentina and Uruguay - are likely to enter the ocean (Jambeck et al., 2015).

The contribution of discarded and lost fishing gear to plastics in the oceans is well-known, e.g., 46% of the Great Pacific Garbage Patch is comprised of fishing nets (Lebreton et al., 2018). Our study adds to an expanding body of evidence that fishing and other vessels also make a major contribution to the other types of plastic polluting the world's oceans and beaches (Díaz-Torres et al., 2017; Monteiro et al., 2018; Ryan et al., 2019; Unger and Harrison, 2016). They underline that waste-management practices on board vessels in the southwest Atlantic need to improve, including the removal of non-degradable items from the contents of galley and mess food-waste bins before the contents are dumped overboard. Unfortunately, MARPOL regulations are difficult to enforce for several reasons; dumping often takes place far from shore and patrol vessels, most litter is impossible to trace to one ship or operator, and the ultimate responsibility lies far away with ship flag states (Chen and Liu, 2013). Increasing awareness by crew and passengers is fundamental to improving practices, should be a key feature of ship inductions, and emphasised on posters on correct waste handling and disposal displayed clearly in galleys, messes, cabins, etc., which may help address chronic garbage mismanagement on particular vessels (Chen and Liu, 2013). Clearly, independent scrutiny is essential, and observers on board vessels for any purpose (e.g. enforcing regulations on fishing, health and safety, customs, tourism, etc.) should be tasked with ensuring compliance with the obligation of every ship of ≥100 gross tonnage or conveying ≥15 persons, to carry and implement a detailed garbage management plan which identifies crew responsibilities (including an Environmental Control Officer) and procedures for all aspects of its handling and storage on board (MARPOL Annex 21, RESOLUTION MEPC.295(71), adopted 7 July 2017). Ports also need to provide economical ways of dealing with garbage returned to shore by vessels, as it is very frequently dumped at sea to avoid paying duties (Chen and Liu, 2013). Although these measures have associated costs, they are far less than the estimated 1–5% or $500–2500 billion of annual marine ecosystem services, globally, that are lost because of current levels of plastic pollution (Beaumont et al., 2019).

CRediT authorship contribution statement

Richard A. Phillips: Conceptualization, Methodology, Formal analysis, Supervision, Writing - original draft, Writing - review & editing. **Claire M. Waluda:** Data curation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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