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Litter and seabirds found across a longitudinal gradient in the South Pacific Ocean

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ABSTRACT

Abundances and composition of marine litter and seabirds were estimated in the central South Pacific (SP) Ocean between the Chilean continental coast and the Easter Island Ecoregion. Litter was dominated by plastics throughout the study area, but the proportion of plastics was higher at sea and on the oceanic islands than in coastal waters and on continental beaches. Litter densities were higher close to the center of the SP subtropical gyre compared to the continental coast. The seabird assemblage was diverse (28 species), and several endemic species were recorded. Seabird abundances were higher in the coastal waters and around Juan Fernández Islands off the continental coast than in the Oceanic and Polynesian sectors. Endangered species breeding on Salas & Gómez Island were observed in the Polynesian sector, which suggests a high potential for negative interactions between seabirds and floating litter, both occurring in high densities in this sector.

1. Introduction

Marine litter is found floating in all oceans and poses a severe threat to marine biodiversity (Sheavly and Register, 2007; Lebreton et al., 2012; Carson et al., 2013). In general, sources of marine debris are land-based or from fishing activities and shipping, and consist primarily of plastics, but also glass, metals, and others materials (UNEP, 2009). Plastics are persistent in the environment and cause injuries and death of diverse marine vertebrates, including fishes (Anastasopoulou et al., 2013), reptiles (Lazar and Gračan, 2011), seabirds (Gray et al., 2012), and marine mammals (Williams et al., 2011), due to entanglement or ingestion (Gregory, 2009; Ryan et al., 2009). Floating debris has been commonly reported from the northern hemisphere (Titmus and Hyrenbach, 2011), but quantitative estimates for the southern hemisphere have only become available recently (Eriksen et al., 2013; Reisser et al., 2013; Thiel et al., 2013; Ryan, 2014).

Model simulations of the distribution of marine litter in the oceans show that floating debris accumulates in the center of the large oceanic gyres (Lebreton et al., 2012; Maximenko et al., 2012; van Sebille et al., 2012; Law et al., 2014; Eriksen et al., 2014). For the S Pacific Ocean, a model by Martinez et al. (2009) had suggested that floating marine litter concentrates between 140°W and 70°W. Recent studies confirm that microplastics are common in waters and on the beaches near the center of the S Pacific gyre (Eriksen et al., 2013; Hidalgo-Ruz and Thiel, 2013). While it can be expected that large marine debris shows a similar distribution pattern, no quantitative estimates are available for the open S Pacific Ocean, because observations of large floating debris are typically restricted to the coastal zones (Hinojosa et al., 2011; Thiel et al., 2013).

Marine wildlife can be significantly impacted by floating litter (Thiel et al., 2011; Hong et al., 2013), and thus it appears important to examine the potential for conflicts. Seabirds spend the majority of their life at sea and thus they are particularly susceptible to marine debris because they ingest floating plastics and other materials while feeding along the sea surface (Ryan, 1987; Auman et al., 1997). Many studies have shown that ingestion has serious consequences, including lesions of the gastrointestinal tract (e.g., perforation, blockage or ulceration), toxic bioaccumulation in organs (e.g., heavy metals, PCB), and ultimately death (Hutton et al., 2008; Gregory, 2009; Tanaka et al., 2013). Also, seabirds are threatened by entanglement in marine debris, impeding them to dive or fly, resulting in infections due to wounds, starvation to death, and drowning (Gregory, 2009). Given the concentrations of floating litter mentioned above, conflicts with wildlife might be especially

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pronounced in the central parts of the open ocean. In particular, species breeding on oceanic islands in this region may be more affected by floating marine debris. As a first step to understand the extent of the problem, herein we examined the potential for conflicts between seabirds and floating litter in the S Pacific. Specifically, we assessed the distribution of floating marine debris and its relation with the diversity and abundance of seabirds across the eastern sector of the central S Pacific Ocean. In order to determine the composition of marine litter and how transport across the sea surface might modify the composition, we compared the types of litter from beaches on oceanic islands and from continental Chile with that of floating litter in the surrounding sectors of the open ocean.

2. Methods

2.1. Study area

We studied the abundance, distribution and composition of both litter and seabirds at sea in the central S Pacific between the S American continent and Easter Island.

Data on floating litter were compared with litter stranded on beaches from the coast of continental Chile, Juan Fernández Island, and Salas & Gómez Island (Fig. 1).

On Juan Fernández Island, Salas & Gómez Island, and at three sites along the Chilean coast (between 30°S and 34°S) we determined the composition of litter on beaches (continental and islands). The smallest litter items counted on beaches were cigarette butts (approximate size: 1.5–2 cm). Litter on beaches was measured using transects perpendicular to the coastline according to survey protocols recommended by Bravo et al. (2009). On each transect a minimum of two stations were surveyed (between 2 and 6 stations). Depending on the width of the beach the distance between sampling stations ranged from 2 m to >20 m. Each station covered an area of 9 m^2, where the litter was counted and classified. Litter densities were expressed as numbers of items per square meter. Data from continental beaches were obtained by volunteers (using the approach by Bravo et al. (2009)) participating in a nation-wide citizen science program that focuses on litter along the Chilean coast (details available at http://www.cientificosdelabasura.cl). The overall composition of the marine litter was compared between oceanic and continental beaches and those found at sea, in order to examine the differences between the two different environments (beaches and open sea).

At sea, we surveyed seabirds and floating litter in the central South Pacific Ocean, covering a total route of ~7500 km, equivalent to the distance between the continent and the islands and back. We traveled aboard the Chilean Navy Patrol Vessel "Piloto Pardo". Data were collected during 16 days (20 November to 11 December 2012) sailing from Valparaíso (33.03°S, 71.62°W) to Salas & Gómez Island (Motu Motiro Hiva Marine Park, 26.47°S, 105.36°W) and Easter Island (27.14°S, 109.43°W), and back to Valparaiso (Fig. 1). We collected information on marine debris and seabirds along three different routes: Valparaíso to Salas &

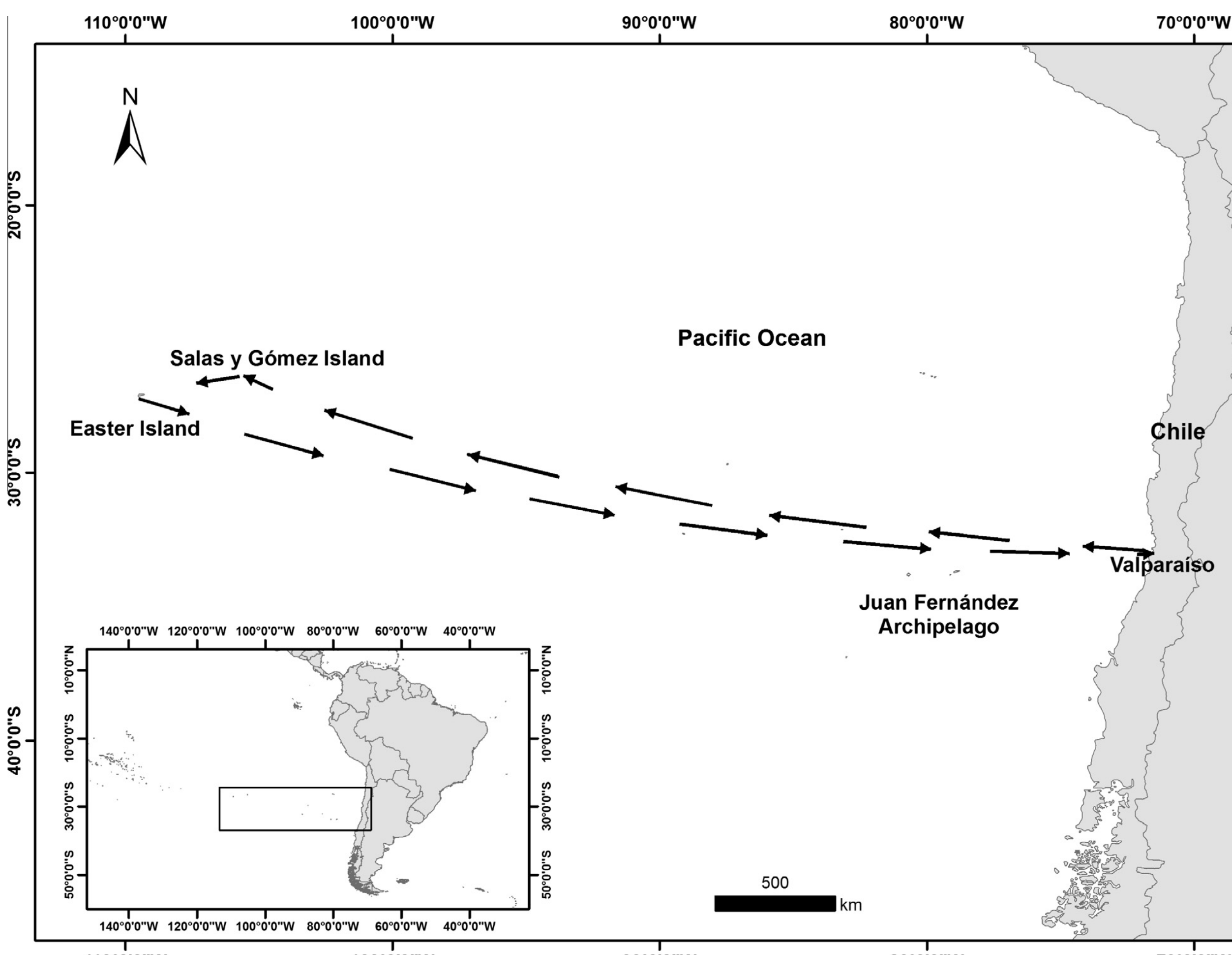

Fig. 1. Map of the study area in the South Pacific Ocean. The black lines show the daylight effective segments of the transect at which seabirds and litter were registered between Valparaíso, Salas & Gómez Island, Easter Island and returning to Valparaiso, in November and December 2012. See text for more details.

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Gómez Island (20–26 November), Salas & Gómez Island to Easter Island (29 November) and Easter Island to Valparaíso (4–11 December). Surveys were conducted while the vessel was sailing at 20 km h^{-1} and the counts were performed from the vessel bridge, ~12 m above the sea surface. Observations were made during daylight hours (8–11 h per day). Because we were aboard of a navy ship, we were not allowed to stay on the deck during naval exercises. When these were finished, we resumed the observations that were made during daylight hours. The average observation time was 4.4 h per day (range: 4–8 h per day). Thus, the effective transect length was 1900 km, during which seabirds and litter were recorded. All sightings were georeferenced using a handheld GPS (Garmin etrex vista HCx).

In order to evaluate the distribution of marine litter and seabirds, the study area was divided into 4 oceanographic sectors based on sea surface temperature (SST) and chlorophyll-*a* (CLH) concentration (Fig. 2). We used monthly average SST (GOES, 5 km resolution) and CHL (Aqua MODIS, 5 km resolution) between 16 November and 16 December 2013. Data were obtained from Ocean Watch (Satellite Environmental Data) available at http://las.pfeg.noaa.gov/oceanWatch/oceanwatch_safari.php. The four sectors were the (1) Humboldt Current, (2) Juan Fernandez, (3) Open Ocean, and (4) Polynesian sector. The first sector basically corresponds to the coastal waters of Chile that are under the influence of the Humboldt Current to ~450 km distance from the coast. The Juan Fernandez sector corresponds to the area around the archipelago but outside of the immediate influence of the Humboldt Current. The Open Ocean sector includes the vast oligotrophic zones in the center of the Pacific Ocean, while the Polynesian sector corresponds to the Easter Island Ecoregion along the Easter Seamount Chain, which includes the waters around Easter Island and Salas & Gómez Island. Comparison of SST between the four sectors (Fig. 2) confirms that waters were warmer in the oceanic (Open Ocean and Polynesian) than in the coastal sectors (Humboldt Current and Juan Fernandez) (Table 1). A shift in chlorophyll-*a* concentration was also observed with higher values in coastal areas than in oceanic areas (Table 1).

2.2. Litter and seabirds at sea

During the trip we counted all marine debris sighted and recorded the position (GPS), type, number and distance of each item. Sizes of items and perpendicular distance to the vessel were estimated according to Thiel et al. (2013). To estimate the total density of marine litter, we used the strip transect method, based on the number of items seen, the perpendicular distance to the vessel for each item, and the transect length (Thiel et al., 2013). Density (D = number of items per km^{-2}) was calculated using the following equation: $D = n/[(w/1000) \times L]$; where n is the number of marine litter observed, w is the maximum distance perpendicular to the line-transect and L is the total length of the transect (in km). A preliminary analysis of the data showed that the probability to detect marine litter items decreased at distances >20 m from the vessel, and therefore we only considered a transect width w of 20 m from the vessel; all items seen at distances >20 m were not included for the density calculation, with the exception of large buoys. For large buoys that could be seen at greater distances, we used a different transect width; for the calculation of buoy

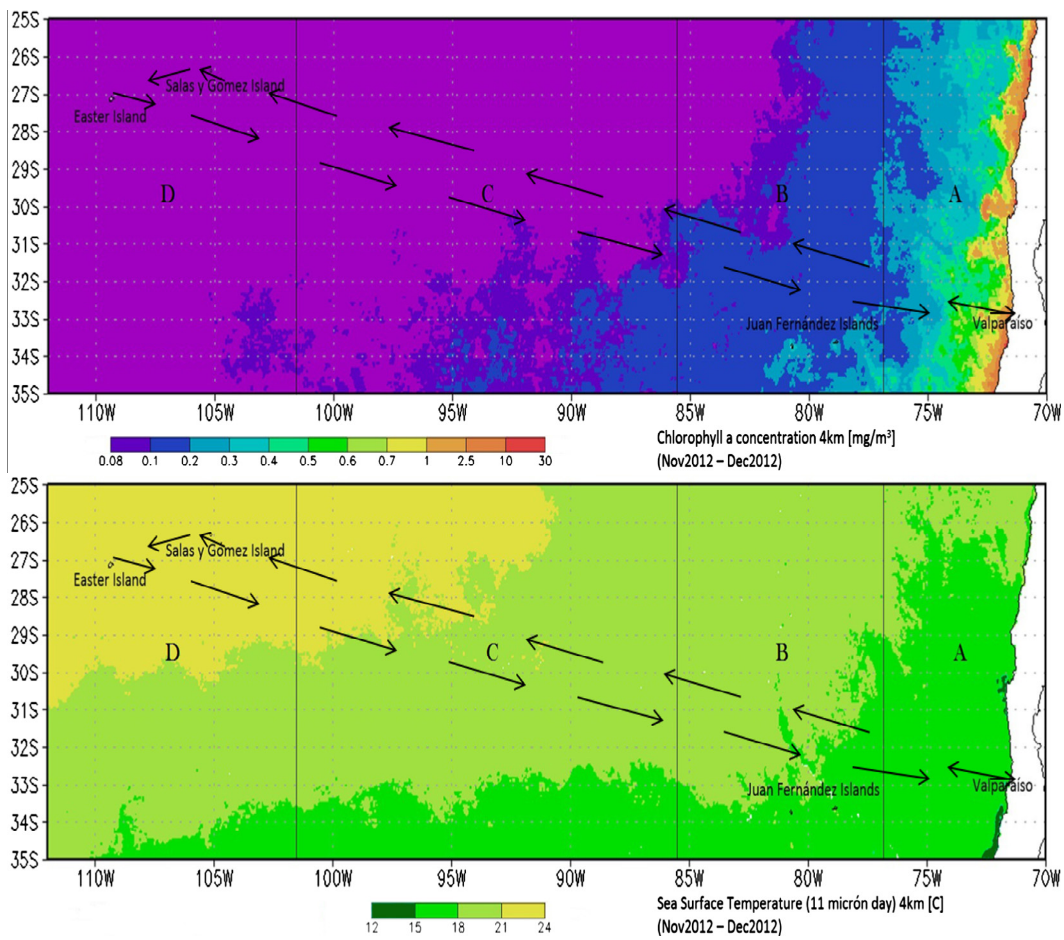

Fig. 2. Chorophyll-*a* concentration (above) and sea surface temperature in the study area, in which four oceanographic sectors were distinguished: (A) Humboldt Current, (B) Juan Fernández, (C) Oceanic, and (D) Polynesian sectors. The arrows show the effective daylight transects during which observations were made.

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Table 1
Sea surface temperature and chlorophyll-*a* concentration in the four study sectors along a longitudinal transect in the Pacific Ocean (see text for details). Data were obtained from Ocean Watch (Satellite Environmental Data) available at http://las.pfeg.noaa.gov/oceanWatch/oceanwatch_safari.php.

Sectors	SST (°C) range	CHL (mg m^{-3}) range
Humboldt Current	14.0–17.8	0.11–13.82
Juan Fernandez	14.9–18.3	0.07–0.44
Oceanic	16.0–21.5	0.004–0.21
Polynesian	18.7–22.9	0.0001–0.06

Table 2
Pairwise comparisons (*F* values and significance) after a permutational analysis of variance (PERMANOVA) comparing the type composition of litter found at sea and on beaches both of the continental Chile and two oceanic islands. Significance (in bold) corresponds to *p*-values with sequential Bonferroni correction.

	Continent	Juan Fernández	Salas & Gómez	At Sea
Continent	–	7.352	9.382	295.9
Juan Fernández	**0.0010**	–	5.282	123.2
Salas & Gómez	**0.0001**	**0.0052**	–	196.1
At Sea	**0.0001**	**0.0001**	**0.0001**	–

densities only those buoys seen within 100 m were included. Litter was classified into 4 categories: plastics (including fragments of various unidentified hard and soft plastic items >2 cm, plastic bags, plastic containers, fishing buoys, lines of polypropylene and fishing nets), paper (principally paper and cardboard), glass (bottles) and metals.

The method used for counting birds at sea was the same as utilized previously in coastal waters of the SE Pacific by Luna-Jorquera et al. (2000) and Weichler et al. (2004). All seabirds on the water surface up to 300 m from the ship's track were counted directly while flying birds were counted using the "snapshot" method, which minimizes the probability of double counting (Tasker et al., 1984). Seabirds were counted from one side of the vessel only and the species identification was made to the lowest possible taxonomic level. Data on seabirds recorded within the strip transect were used to estimate density, calculated as numbers of birds per km^2 (total number of individuals sighted/(transect distance $\times$ 300 m; Titmus and Hyrenbach, 2011). Both litter and seabirds were counted and summarized in 10 min intervals; therefore the total distances covered during daylight (1900 km, see above) yielded a total of 424 transects used for calculations.

2.3. Statistical analyses

Differences in the composition of litter categories on beaches were evaluated using a one-way permutational analysis of variance (PERMANOVA, 10,000 runs), and a posteriori tests based on the Bray–Curtis index of similarity. Litter densities were transformed using the fourth root of the proportions of density in order to meet the assumption of homoscedastic variances. The relative contribution of each particular litter category to differences in composition was evaluated using a similarity percentage analysis (SIMPER). To examine variations in the litter and seabird abundances between the four oceanographic sectors (Fig. 1), we used one-way PERMANOVA (10,000 runs), and a posteriori tests based on the Bray–Curtis index of similarity. Analyses were carried out using the free software PAST v. 2.12 (Hammer et al., 2001). Because of the large number of zeros, overall statistics (mean and standard deviation) for the data distribution both of litter and seabirds at sea, expressed as items km^{-2} and birds km^{-2}, respectively, were calculated using the function *gamlss* implemented in the free software R, which is a generalized additive model for location scale and shape of distribution data. After visual inspection of data and residuals, we determined that the density of litter at sea conforms better to a zero-inflated logarithmic distribution. Figures (except Figs. 1 and 2) were made using the function *ggplot* for the software R.

3. Results

3.1. Composition of litter on beaches

The total numbers of items found on beaches were 1435 on the continental coast, 77 on Juan Fernández Island, and 276 on Salas & Gómez Island. The proportions of the different litter items observed in this study were significantly different among beaches and those floating at sea (PERMANOVA, $F = 93.66$, $P < 0.0001$, Table 2 and Fig. 3). The average dissimilarity among the different compartments was 83.3% (SIMPER all groups). Plastic was the most abundant item, which mostly contributed to differences (SIMPER, 56.4%) among sites, followed by paper (19.8%), glass (14.8%) and metal (9.0%). On Salas & Gómez Island no paper was found, but fragments of glass ($n = 21$), glass-bottles ($n = 3$) were more common than on the other beaches (Table 3). Metals found on Salas & Gómez Island consisted of 1 aerosol container and 9 steel buoys. The proportion of paper was higher in the continental coastal sectors than on the islands.

3.2. Litter at sea

Litter was found in only 85 (~20%) of the 424 transects surveyed at sea. A total of 146 items were found (see Table 3), comprising diverse types of plastic, most of which were plastic fragments larger than 2 cm (62.3%). Other plastic items were lines (19.2%), buoys (6.1%), nets (4.1%), and bottles (3.4%). Other items such as buckets, plastic drums, plastic cups, and sacks, were observed infrequently (<4.8%). The abundance of floating litter sighted within transects was 0.99 ± 0.78 items km^{-2} (mean and standard deviation for a Zero Adjusted Logarithmic Distribution, $P > 0.05$). Litter densities ranged between 0 and 51.68 items km^{-2} (Fig. 4). The abundance of floating litter was significantly different between the four oceanographic sectors (PERMANOVA test, $F = 12.75$, $P < 0.0001$). A posteriori tests indicated that litter density was higher in the Polynesian sector, but no differences were detected between the Humboldt Current and Open Oceanic sectors. Around Juan Fernández Island no floating litter was registered. The incidence of litter abundance in the Humboldt Current, Oceanic and Polynesian sectors is more clearly observed when their frequency distribution is compared (Fig. 5). The frequency of occurrence and amount of litter were higher in the sectors closest to the subtropical Gyre (between 99°W and 109°W) than in areas near the continent.

3.3. Seabirds at sea

We recorded a total of 426 individuals and 28 species, 11 of them breeding on the Chilean oceanic islands (see Supplement 1). Seabirds were observed on 65% of all transects. The seabird assemblage was represented by five orders, which, in order of importance were, Procellariiformes (60.7%), Charadriiformes (17.9%), Suliformes (14.2%), Pelecaniformes (3.6%) and Phaethontiformes (3.6%). Five species (Juan Fernandez Petrel, Stejnegeŕs Petrel, Pink-footed Shearwater, Kelp Gull and Sooty Shearwater) accounted for ~70% of all identified birds. The most abundant species differed in abundance between the four oceanographic sectors (Table 4). In the Humboldt Current the dominant species were the Pink-footed Shearwater, the Kelp Gull and the Sooty Shearwater. Around Juan Fernandez Island and in the Open

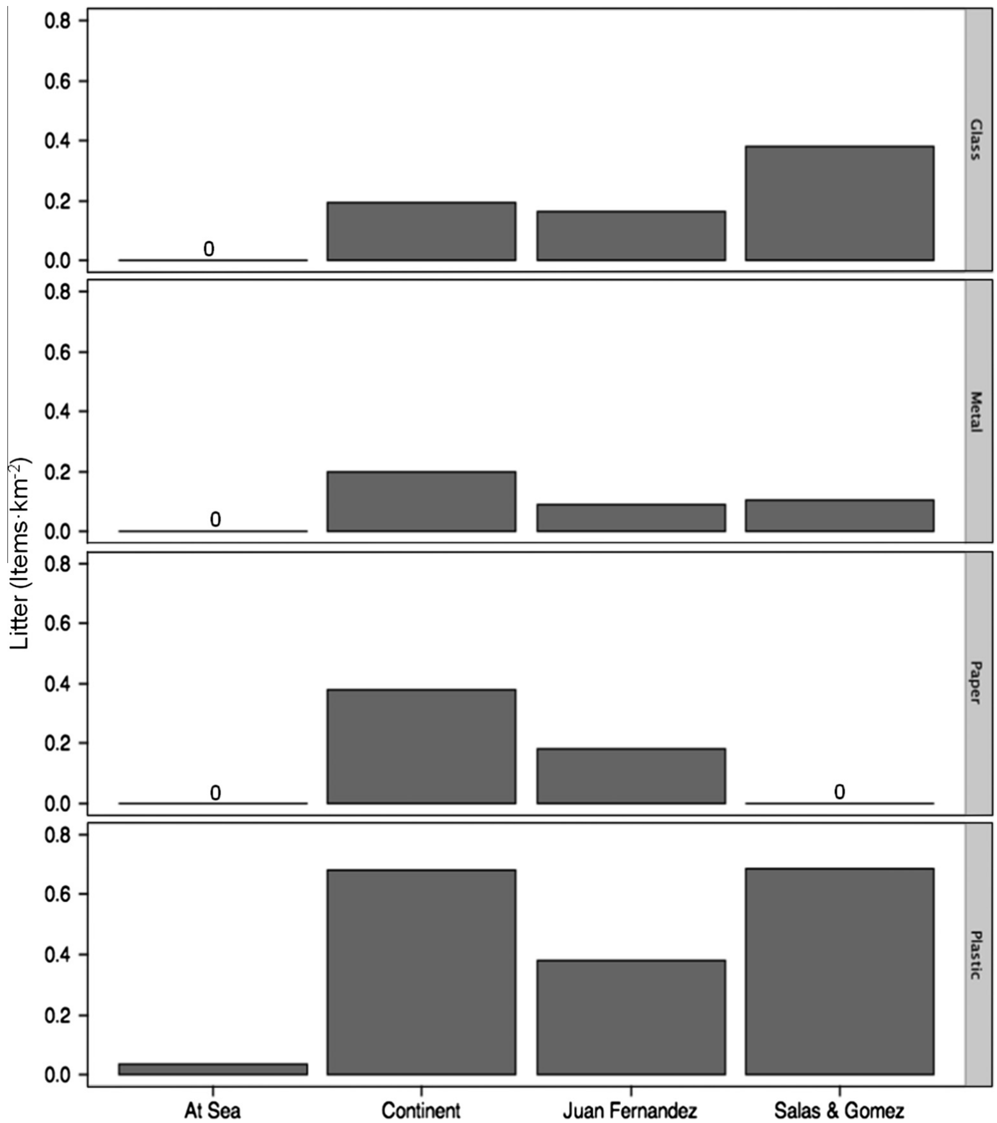

Fig. 3. Mean abundance of marine litter (items km^{-2}) on beaches from the continent (Chilean coast), oceanic islands and floating at sea. Values after SIMPER analysis for all groups using Bray–Curtis index. Overall average dissimilarity = 86.34%.

Oceanic sector the most abundant seabird was the Juan Fernandez Petrel. In the Polynesian sector, three species, the Polynesian Storm Petrel, Grey Noddy and Juan Fernandez Petrel, were the most abundant.

The mean density of birds was 0.79 ± 0.66 birds km^{-2} (mean and standard deviation for a Zero Adjusted Logarithmic Distribution, $P > 0.05$), with ranges between 0 and 53.07 birds km^{-2}. Highly significant differences were found between sectors for the abundance of seabirds (PERMANOVA $F = 63.39$, $P = 0.0001$). A posteriori tests determined that there were no significant differences between the Humboldt Current and Juan Fernández, and also the abundances between the Open Ocean and Polynesian sectors did not differ from each other (Fig. 6).

4. Discussion

4.1. Litter composition and abundances

Our study showed that plastic was the most common litter category encountered on the beaches, and, as expected, plastic was the only litter type observed at the sea surface. The proportions of plastic found on beaches in the coastal sector (65%) are similar to those reported for other regions of the Pacific Ocean. For example, for beaches from continental Chile, the proportions of plastics ranged between 20% and 80% (Bravo et al., 2009; Thiel et al., 2013; Rech et al., 2014). On Australian beaches, Edyvane et al. (2004) reported that 70.4% of litter items were plastics. Similar plastic proportions were found in Japan (72.9%, Kusui and Noda, 2003), Brazil (69.8%, Santos et al., 2005), and the Gulf of Oman (61.8%, Claereboudt, 2004). While proportions of plastic were lower on beaches from northern South China Sea (Zhou et al., 2011), Brazil (Neto and da Fonseca, 2011), and Mexico (Silva-Iñiguez and Fischer, 2003), plastics were still the dominant litter items. In examining the litter found on the Salas & Gomez Island, it is most likely that most of them originated from fishing activities. From the 277 items of litter found here, 8.7% correspond to fragments of glass containers probably from shipping activities. Metal items (3.6%) are mainly steel buoys, and plastic litter (87.6%) corresponds to plastic fragments, buoys, lines, nets and trays. This high proportion of plastic is slightly lower than the value (91.1%) reported for Midway Atoll, which is located in the North Pacific Gyre and thus

Table 3
Number of items and percentage of marine litter observed both at sea and on beaches in the study sectors (see text for details). At sea data are from: HC = Humboldt Current, JF = Juan Fernández, O = Oceanic, P = Polynesian. Beaches are: C = Continental coastal, SG = Salas & Gómez Island. Note that in the Juan Fernández sector no litter was observed at sea. For Continental beaches (C) we counted litter grouped in only four classes (plastic, papers, metals and glass).

Litter	Sea surface			Beaches		
	HC *n* (%)	O *n* (%)	P *n* (%)	C *n* (%)	JF *n* (%)	SyG *n* (%)
Plastics						
Fragments	2 (25)	40 (62)	49 (67)	873 (61)	36 (47)	90 (33)
Plastic bags	0 (0)	0 (0)	0 (0)		0 (0)	0 (0)
Lines	0 (0)	8 (12)	20 (27)		3 (4)	18 (7)
Sacks	0 (0)	1 (2)	1 (1)		0 (0)	0 (0)
Net	0 (0)	5 (8)	1 (1)		0 (0)	1 (0)
Buoys	0 (0)	8 (12)	1 (1)		0 (0)	97 (35)
Plastic Bottle	3 (38)	1 (2)	1 (1)		1 (1)	22 (8)
Plastic bucket	0 (0)	1 (2)	0 (0)		0 (0)	0 (0)
Plastic drum	1 (13)	1 (2)	0 (0)		0 (0)	0 (0)
Plastic cup	1 (13)	0 (0)	0 (0)		0 (0)	0 (0)
Others						
Papers				291 (20)	10 (13)	0 (0)
Metals				105 (7)	6 (8)	10 (4)
Glass fragments				166 (12)	13 (17)	24 (9)
Polystyrene					8 (10)	13 (5)
Wood	1 (12)	0 (0)	0 (0)		0 (0)	1 (0)
Total	8	65	73	1435	77	276

also exposed to marine litter originating from fishing and shipping activities (Ribic et al., 2012). Because of their position in the South Pacific Gyre (see Eriksen et al., 2014), floating debris is accumulating on Salas & Gomez Island implying a high risk for breeding seabirds (Fig. 7).

On continental beaches, the litter composition can be associated with different factors such as proximity to urban centers, industrial and recreational areas, shipping lanes, and fishing grounds. The knowledge of the sources of marine litter is important because it can serve as the primary foundation for management decisions to prevent problems caused by marine debris (Sheavly, 2010). Usually the litter items, which are arriving from distant points (Ryan, 2014) on oceanic island located near the center of gyres, are highly eroded or fragmented. It is thus difficult or impossible to determine their specific sources, although some items (i.e. buoys, nets and fishing lines) stranding on oceanic islands are clearly originating from fishing activities (Ribic et al., 2012).

The results obtained in the present study revealed clear differences between the abundance of floating litter, where abundances were highest in the subtropical gyre (between 99°W and 109°W, waters near Easter Island and Salas & Gómez Island). Since they degrade slowly and have a high buoyancy, many plastic items travel for thousands of km with oceanic currents (Sheavly and Register, 2007), finally accumulating in the oceanic gyres (Law et al., 2010; Goldstein et al., 2013; Cózar et al., 2014; Eriksen et al., 2014). Recently, estimates in the S Pacific determined higher abundance of floating microplastics between ~97°W and ~111°, where ~88% of the total was counted (Eriksen et al., 2013). Our results are well supported by oceanographic models simulating the trajectories of floating marine litter, which show an accumulation of debris in the eastern-central region of the S Pacific subtropical gyre (120–80°W; 20–40°S), resulting from converging Ekman and geostrophic currents (Martinez et al., 2009; Maximenko et al., 2012; Lebreton et al., 2012; van Sebille et al., 2012).

While our results confirmed the accumulation of plastic litter in the oceanic regions, especially in the Polynesian sector, the observed densities of floating litter (ranges between 0 and 51.68 items km^{-2}) in our study were low compared with values reported for other areas. For example, in the NE Pacific Titmus and Hyrenbach (2011) reported higher debris densities ranging from 0 to >10,000 items km^{-2}. In Southeast Asia, in the Straits of Malacca and the Bay of Bengal, Ryan (2013) reported similar values as found in our study, but he also remarked high variations of

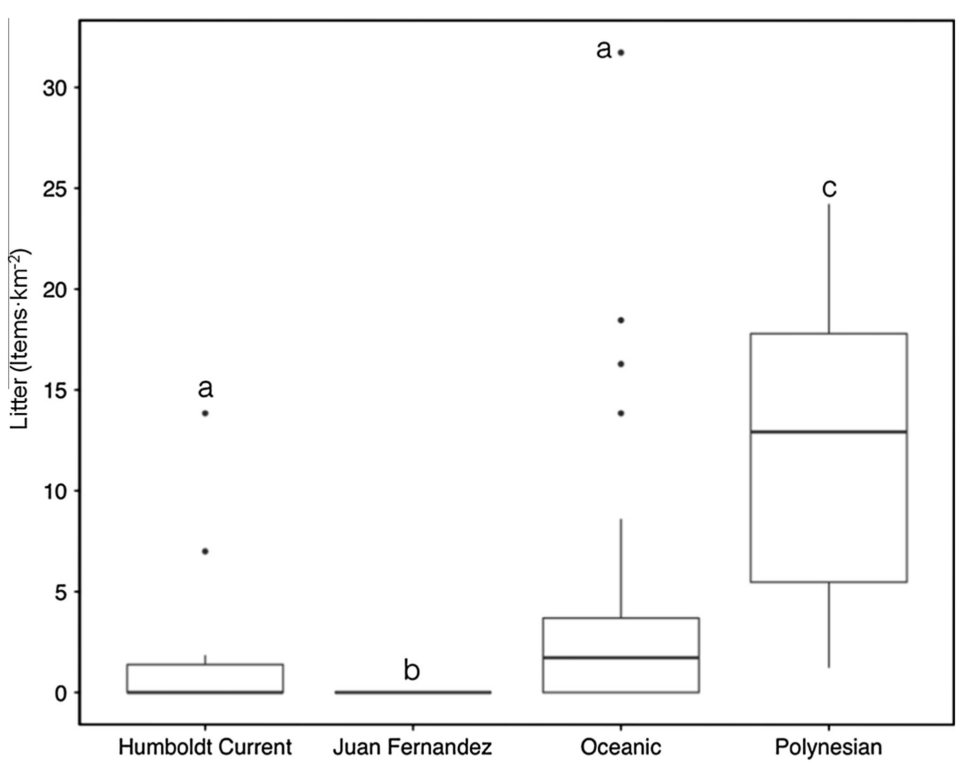

Fig. 4. Litter abundance in four oceanographic sectors along a longitudinal gradient in the South Pacific Ocean (see Figs. 1 and 2). Letter above box-plot indicates significance after a pairwise comparisons test. Outliers > 30 item km^{-2} were excluded to facilitate visual comparison.

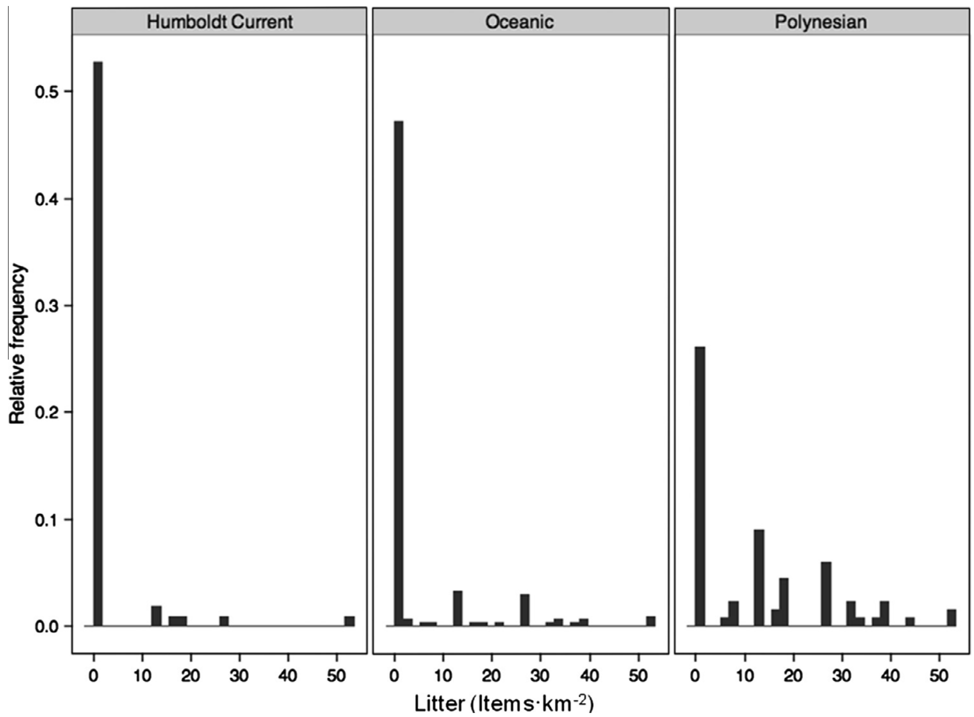

Fig. 5. Relative frequency of floating litter abundance in three sectors of the Pacific Ocean recorded between Valparaiso and Easter Island (see Fig. 1). Please, note that the Juan Fernandez sector is not included in this analysis because no floating litter was seen in this sector.

Table 4
Count and relative abundance of the most abundant seabird species per sector. The total number of seabirds registered and effectively identified in the study area was 405 individuals. Here, Count is the number of birds registered by species in each sector, and Percentage was calculated from the total seabirds.

Sector	Species	Count	Percentage
Humboldt Current	Pink-footed Shearwater	27	6.7
	Kelp gull	27	6.7
	Sooty shearwater	25	6.2
	Red Phalarope	16	4.0
	Peruvian Pelican	10	2.3
Juan Fernández	Juan Fernandez Petrel	120	29.6
	Stejnegeŕs Petrel	13	3.2
	White-bellied Storm-Petrel	6	1.5
	Black-browed Albatross	4	1.0
	Pink-footed Shearwater	3	0.7
Oceanic	Juan Fernandez Petrel	35	8.6
	De Filippi's Petrel	16	4.0
	White-bellied Storm-Petrel	6	1.5
	Kermadec Petrel	2	0.5
	Masked Booby	1	0.3
Polynesian	Polynesian Storm Petrel	6	1.5
	Grey Noddy	6	1.5
	Juan Fernandez Petrel	6	1.5
	Red-tailed Tropicbird	1	0.3
	Brown Noddy	1	0.3

marine litter densities with ranges between 1–∼1000 and 0–∼100 items km^{-2}, probably related to the distance from sources and wind-related movements of litter (e.g. small pieces of foamed polystyrene and empty bottles). The litter abundances observed herein were similar to those reported by Ryan (2014) for the S Atlantic, but he remarked that his survey did not cover the presumed accumulation area in the S Atlantic subtropical gyre, where abundances likely are higher. Some of the reasons for lower abundances of floating litter in the central S Pacific compared to the subtropical gyres in the northern hemisphere might be related to lower population density, less industrial activity and lower shipping traffic in the southern hemisphere (see also model outcomes from van Sebille et al., 2012).

4.2. Seabirds in the South Pacific

The South Pacific has been identified as one of the most important regions in terms of richness and abundance of seabirds. The oceanic islands of Chile (e.g., Desventuradas Islands, Juan Fernández Island, Salas & Gómez Island and Easter Island) are important breeding sites for several endemic seabird species (Schlatter and Simeone, 1999). Among the seabirds observed in our study, the Juan Fernandez petrel was the most abundant species. This petrel breeds only on Juan Fernández Islands off the coast of Chile (BirdLife International, 2014). Because seabirds are restricted to land for reproduction and are central place foragers, it is reasonable to expect that for some species the distribution patterns at sea reflect the location of breeding colonies (Ballance et al., 1997). Our results on abundance and distribution patterns clearly show that this prediction is supported for the Juan Fernandez petrel, because the highest abundances were determined in areas near the nesting islands. Oceanographic factors and specially food availability strongly influence the patterns of abundance and at sea distribution of seabirds (Weichler et al., 2004). Thus, with the exception of many Procellariiformes, seabirds can only breed on an island if they can successfully forage in surrounding waters. Therefore, the high productivity in areas closer to the coast (Juan Fernandez and Humboldt Current) may be responsible for the higher abundance and diversity of seabirds observed in these sectors.

Owing to their remoteness, Easter Island and Salas & Gómez Island are at the margin of the distributional range of several tropical seabird species. The number of extant breeding seabirds both on Easter and Salas & Gómez islands is estimated at seven (Jaramillo et al., 2008), and eleven species (Vilina and Gazitua, 1999), respectively. However, for Easter Island this figure is only

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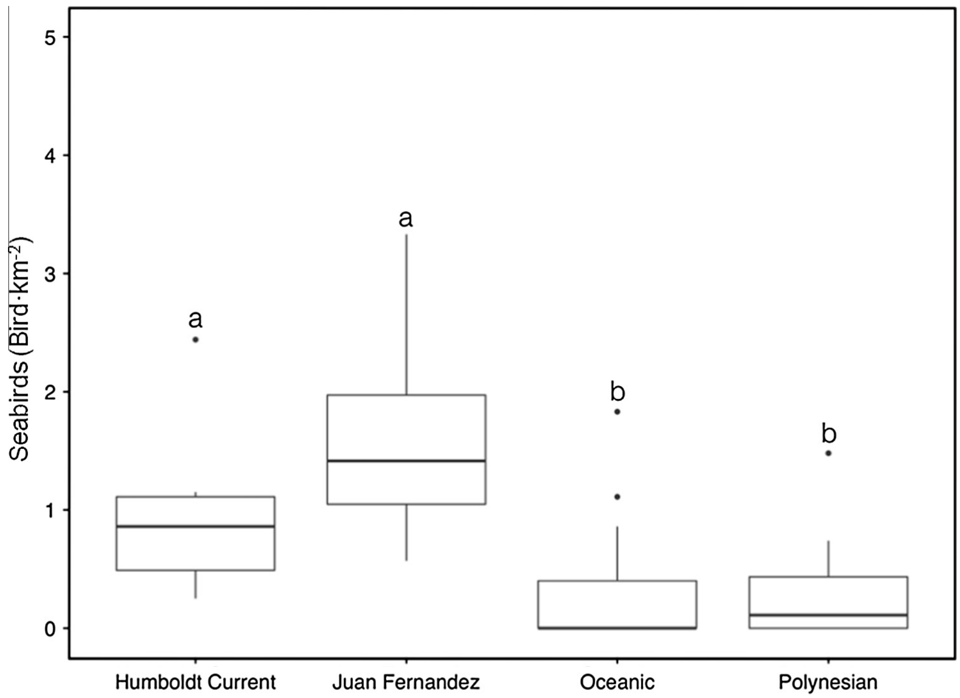

Fig. 6. Seabird abundance in four oceanographic sectors along a longitudinal gradient in the South Pacific Ocean (see Figs. 1 and 2). Letter above box-plot indicates significance after a pairwise comparisons test.

a small percentage (28%) of the 25 seabird species that were resident on the island in prehistoric times and went extinct due to human perturbation (Schlatter, 1984; Steadman, 1995). In contrast, Salas & Gómez Island has never been inhabited by humans, is free of introduced mammals, and is an important breeding site for several tropical seabird species (Schlatter, 1984), such as the Polynesian Storm Petrel, Christmas Shearwater and Blue grey noddy (Vilina and Gazitua, 1999). The major threat to these populations breeding on islands close to the subtropical gyre appear to be the large amounts of floating litter in the surrounding waters.

4.3. Interactions between marine litter and seabirds

Several studies worldwide have reported negative interactions between floating litter and seabirds. These problems include entanglement, plastic ingestion and contamination by heavy metals and organochlorines (Ryan, 1987; Gregory, 2009). In the present study we observed some fishing nets at sea, but no entangled seabirds were seen at sea (but see Fig. 7). Our study found that floating plastics are most abundant in the Polynesian sector and on beaches of Salas & Gómez Island, which is approximately 300 km ENE of Easter Island and is part of the Motu Motiro Hiva Marine Park. Salas & Gómez Island is an important breeding site for several seabird species (Harrison, 1988; Vilina and Gazitua, 1999). It is highly likely that interactions between seabirds and floating plastic are common in areas near Easter Island and Salas & Gómez, because these seabirds commonly ingest plastic items or incorporate them in their nests (Fig. 7), particularly Great Frigatebirds and Masked Boobies (e.g. Votier et al., 2011). Titmus and Hyrenbach (2011) found positive relationships between floating debris and seabird abundance for three species (e.g., Black-footed Albatross, Cook's Petrel and Red-tailed Tropicbird) and two other species from the order Procellariiformes. On Salas & Gómez Island we have collected 10 dead specimens of the Polynesian Storm petrel (*Nesofregetta fuliginosa*, classified as endangered according to IUCN (2014)), and all stomachs analyzed contained plastic (D. Miranda, unpublished data).

Larger plastic items are also frequently incorporated in seabird nests (Votier et al., 2011; Bond et al., 2012; Verlis et al., 2014). This can lead to entanglement of adults and nestlings (Votier et al., 2011). Incidences of nests with plastic litter are particularly high in areas with abundant input of litter, e.g. due to fisheries (Bond et al., 2012). Similar impacts are also expected in the Polynesian sector where large amounts of floating plastics were found and where several oceanic seabirds are nesting; in fact, plastic litter is frequently observed in their nests (Fig. 7).

The effects of plastic particles ingested by seabirds have been well documented (Derraik, 2002; Gregory, 2009). In some cases, the stomachs suffer ulcers and the intestines are obstructed, mainly when large fragments were ingested. Recently, Lavers et al. (2014) found that Flesh-footed Shearwaters (*Puffinus carneipes*) with high levels of ingested plastic exhibited reduced body condition and increased contaminant load.

4.4. Conclusions and recommendations

The results of the present study represent a first approximation on marine litter accumulations across a wide area of the South Pacific Ocean and its relation to the distribution of seabirds on oceanic islands of Chile. The accumulation of marine litter in the Polynesian sector likely results from the transport of plastic particles through the oceanic current system to the South Pacific Subtropical gyre. Repeated surveys of the distribution, accumulation and types of floating litter in the S Pacific will help to understand whether the observed patterns persist over time or whether they may vary due to temporally variable input of litter. Furthermore, tracking litter items over time will enhance our understanding of litter movements at sea and identification of specific litter items (e.g. from fisheries) will aid in the determination of specific sources of marine pollution. Finally, it is very likely that interactions between seabirds and floating litter increase in

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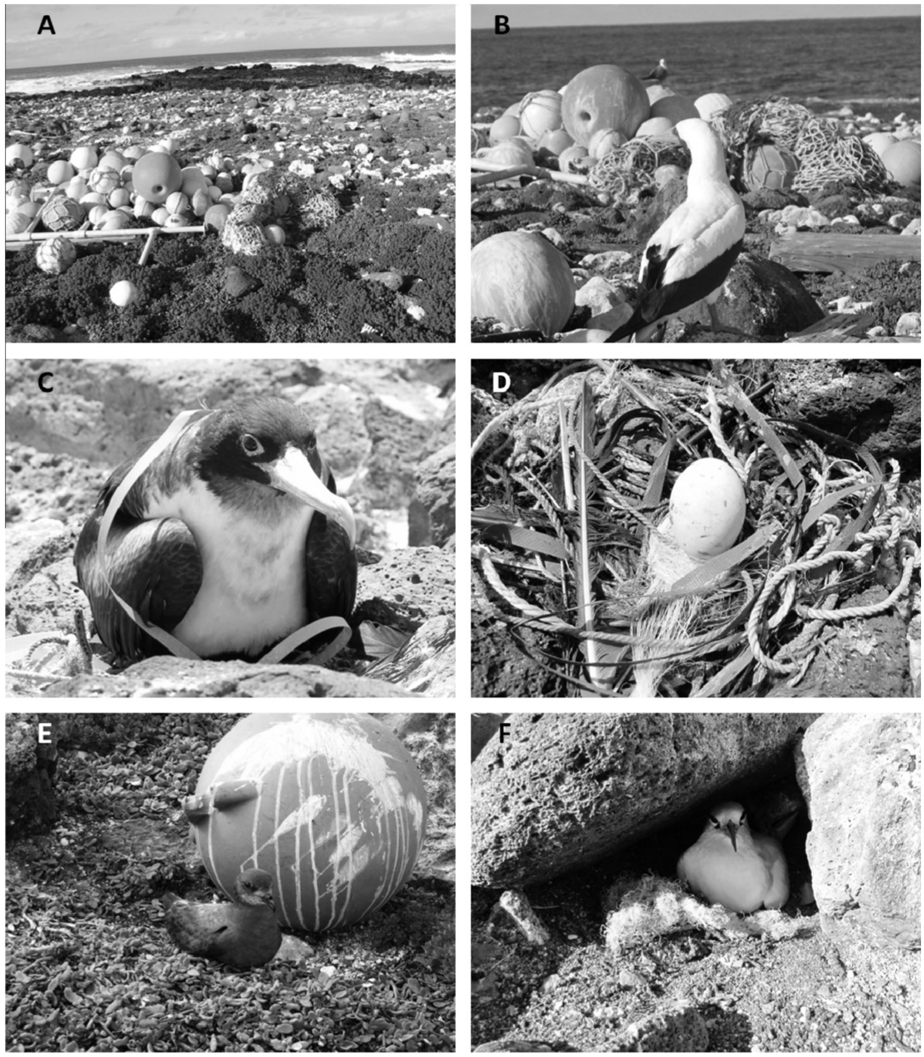

Fig. 7. The photographs show marine litter and seabirds observed on Salas y Gómez Island: (A) Plastic and metal buoys, (B) Masked Booby and litter around their nests, (C) Great Frigatebird entangled with plastic tape, (D) Plastic used as nesting material by Great Frigatebird, (E) Murphy's Petrel and plastic buoy, (F) Remains of fishing net in nest of Red-tailed Tropicbird.

the Polynesian sector and that negative effects may be most severe for species breeding on Easter Island and Salas & Gómez Island. Therefore, studies of the ecological consequences of marine litter on nesting seabirds on these oceanic islands are needed. Overall, this study once more confirms that more efficient measures to reduce the input of plastic litter to the oceans are urgently needed.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2015.05.021.

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