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ORIGINAL RESEARCH

Floating marine debris in two pelagic ecosystems of the southwestern Atlantic off Argentina

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ABSTRACT. In 2012 and 2013, observational surveys from seismic vessels were conducted to evaluate the abundance and composition of floating marine debris (FMD) in the east of Tierra del Fuego (TDF), Argentina, and the Brazil/Malvinas Confluence zone (BMC), respectively. The mean abundance of FMD varied significantly between sampled ecosystems, with higher loads in TDF (mean abundance = 6.15 ± 8.84 items) when compared to BMC (3.31 ± 6.83 items). Plastics dominated the composition of FMD at both ecosystems (> 80%), followed by foamed plastics. Within the plastic category, bags were the most abundant item, followed by wrappers, and bottles, among others. According to its color, white/clear, and multicolor debris were the most abundant. The main presumed source of FMD was domestic activities, followed by fisheries-related, and construction. This is the first study demonstrating the utility of using seismic vessels as a platform for monitoring FMD in waters within the Argentine continental shelf and adjacent waters.

Key words: Environmental pollution, southwest Atlantic Ocean, plastic, Argentine continental shelf.

Desechos marinos flotantes en dos ecosistemas pelágicos del Atlántico Sudoccidental frente a Argentina

RESUMEN. En 2012 y 2013, se realizaron estudios de observación desde buques sísmicos para evaluar la abundancia y composición de desechos marinos flotantes (FMD) en el este de Tierra del Fuego (TDF), Argentina y en la zona de confluencia Brasil/Malvinas (BMC), respectivamente. La abundancia media de FMD varió significativamente entre los ecosistemas muestreados, con cargas más altas en TDF (abundancia media = 6,15 ± 8,84 elementos) en comparación con BMC (3,31 ± 6,83 elementos). Los plásticos dominaron la composición de los FMD en ambos ecosistemas (> 80%), seguidos del poliestireno expandido. Dentro del rubro de plásticos, las bolsas fueron el ítem más abundante, seguido de envoltorios y botellas, entre otros. Según su color, los restos blancos/transparentes y multicolores fueron los más abundantes. La principal fuente presunta de FMD fue la actividad doméstica, seguida de las relacionadas con la pesca y la construcción. Este es el primer estudio que demuestra la utilidad de los buques sísmicos como plataforma para monitorear los FMD en aguas dentro de la plataforma continental Argentina y aguas adyacentes.

Palabras clave: Contaminación ambiental, Océano Atlántico Sudoccidental, plástico, plataforma continental argentina.

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INTRODUCTION

Anthropogenic debris in the marine environment (often referred as to marine debris) has arguably become the main environmental issue of the XXI century (Bergmann et al. 2015). This is because pollution by marine debris, of which plastics comprise the main fraction, is ubiquitous, conspicuous and pervasive. Moreover, plastic debris is considered to be relative stable and highly durable, potentially enduring thousands of years (Barnes et al. 2009). Marine debris are persistent manufactured or processed solid material discarded, disposed or abandoned in the marine and coastal environment (Coe and Rogers 1997; Galgani et al. 2010; Bergmann et al. 2015). This debris can be categorized according to the type of material and assigned to sources derived from human activities such as recreational, fishing, sewage-related and shipping, though other sources include storm water and urban runoff, and riverine input (Somerville et al. 2003; Storrier et al. 2007; Chesire et al. 2009).

First records of marine debris in the oceanic realm date back between 1960s and 1970s (Holgersen 1961; Caldwell et al. 1965; Brongersma 1968; Carpenter and Smith 1972). In modern days, pollution by marine debris, particularly plastics, has been reported in virtually all of the World´s oceans (Gregory and Andrady 2003; Cózar et al. 2014). This is partially because of human population increase coupled with an intense consumption and rapid disposal of plastic products, thus causing debris to appear in remote places (Bergmann et al. 2017; Barnes 2018; Lacerda et al. 2022). Jambeck et al. (2015) estimated that by 2025 marine litter in the ocean would reach between 100 and 200 million tons, whereas new modelling predicts between 20-53 to 90 million tons' year^{-1} by 2030 (Borrelle et al. 2020). In the marine environment, some debris may sink to the sea floor while other might remain afloat for various periods. Those debris that remain afloat, considered hereinafter as floating marine debris (FMD), are chiefly sighted either within main shipping routes and near-shore coastal waters in close proximity to urban regions or in relation to major ocean current systems (Thiel et al. 2003; Shiomoto and Kameda 2005). Plastic debris comprises a high proportion of FMD in diverse oceanic regions. This phenomenon has been observed in the Mediterranean Sea (Morris 1980; Lambert et al. 2020), the SE Pacific off the Chilean coast (Thiel et al. 2003; Hinojosa and Thiel 2009; Ahrendt et al. 2021), the NW Pacific Ocean (Yamashita and Tanimura 2007), the Mexican Central Pacific (Díaz-Torres et al. 2017), the Black Sea (Miladinova et al. 2020), and other locations (Van Sebille et al. 2015). Among FMD, the fraction comprised either by micro-litter (< 5 mm) and macro-litter (> 5 to 25 mm, Galgani et al. 2013) can cause severe injuries to marine organisms, especially marine megafauna (turtles, seabirds and marine mammals), either by entanglement in or by ingestion of FMD (Jacobsen et al. 2010; Reeves et al. 2013; Garcia Garin et al. 2020; Roman et al. 2020). A recent review documents marine debris (FMD and others) affecting at least 914 species (Kühn and Van Franeker 2020). Lethal and sub-lethal individual-level effects included drowning, starvation, gastrointestinal tract damage, malnutrition, physical injury, reduced mobility, and physiological stress, resulting in reduced energy acquisition and assimilation, compromised health, reproductive impairment, and mortality (Senko et al. 2020).

Despite pollution by FMB being a major concern for the public as well as for scientists and policymakers worldwide (Kühn and Van Franeker 2020), there are geographical gaps that need to be addressed, specifically in the Southern Hemisphere. There, standardized field techniques and data recording and processing are rare, thus turning comparisons between regions difficult (Gregory and Ryan 1997). Literature specifically focused on FMD in such region is biased towards the South Atlantic gyre as far south as 34° S-35° S (Ryan 2014; Ryan et al. 2019) or in the waters around South Africa (Morris 1980; Ryan 1988; Collins and

Hermes 2019). Therefore, further data are needed regarding the occurrence of FMD in other areas within the South Atlantic. In particular, the region covered by the Argentine continental shelf is one of the most extensive marine areas of the world with c. 1,000,000 km^2 and is comprised largely by an underwater plateau of less than 100 m deep. This area is a ground for large, high-seas commercial fisheries, including longliners, trawlers and jiggers, totaling some 400 vessels (Prosdocimi et al. 2022). Besides, the area is also targeted by offshore seismic exploration, commencing some 40 years ago (Ewing et al. 1963; Ludwig et al. 1968; Lesta 2002). The coastal marine ecosystem of Argentine is home to a large diversity of small-scale fisheries with a long history of coastal fishing (Mateo 2004; Perrotta et al. 2007), particularly at northern Patagonia, where the largest urban regions are settled as well as the main commercial ports and harbors (Rozycki et al. 2021).

While conducting surveys of marine megafauna (seabirds and mammals) around commercial seismic vessels in the waters of the Argentine continental shelf and adjacent international waters, floating marine debris was sighted and documented. This study presents novel information on the occurrence, distribution and composition of floating marine debris (FMD) in the target area, particularly in two contrasting marine ecosystems: (i) the Tierra del Fuego basin in the Argentine Sea; and (ii) the Brazil-Malvinas Confluence in international waters. We hypothesized that in the Tierra del Fuego ecosystem, a higher abundance of marine floating debris would be expected due to its proximity to the coastline.

MATERIALS AND METHODS

Study area

The sightings of floating marine debris (FMD) occurred in the high seas of two distinct areas. The first area, referred to as TDF, was situated east of Tierra del Fuego (54° S-55° S) on the southern section of the Argentine continental shelf during the spring of 2012. The second area, known as BMC, was in relative proximity to the Brazil/Malvinas Confluence zone (35° S-38° S) on the northern portion of the Argentine continental shelf during the spring of 2013 (Figure 1).

Samplings and composition of floating marine debris

Sightings of FMD were conducted aboard two commercial seismic vessels with the purpose of locating offshore oil fields. Seismic vessels (Western Geco Vespucci and Western Geco Triton) operated from 29 September to 6 November 2012 and from 6 October 2013 to 31 December 2013 (TDF and BMC, respectively). Seismic exploration performed on TDF was conducted over 77 days at sea, covering 11,398 km^2 (Table 1) (for further details see Seco Pon et al. 2019). The ship (Vespucci) departed from Comodoro Rivadavia, Santa Cruz Province (45° 52′ 00″ S, 67° 30′ 00″ W) and returned to Ushuaia, Tierra del Fuego Province (54° 48′ 30″ S, 68° 18′ 30″ W). While the other ship (Geco Triton) operated on BMC, also conducting seismic exploration, over 92 days at sea and covering 2,000 km^2. It departed and returned to Montevideo Port (Uruguay). Both vessels sailed continuously while collecting seismic data at speeds varying between 3 to 5 knots (except during bunkering, rough weather, and when shifting stations), though observations on FMD were conducted only during daylight hours while ships were underway, and were performed from the bridge wings, 17-21 m above sea level. Overall, the total observation time (1,455 h) consisted of 126 observation bouts (with a mean observational bout estimated at 11.32 ± 1.22 h) performed between 6:00 am to 20:30 pm local time (both vessels combined).

During navigations, two experienced observers continuously surveyed both sides of the vessels (one operator on each side) in an unobstructed 180°

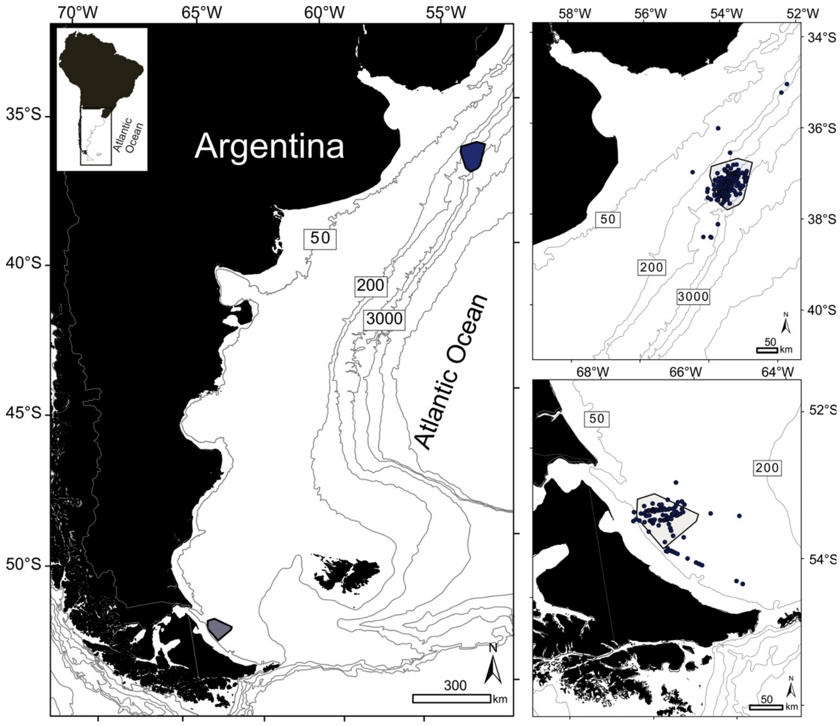

Figure 1. Study area (left). Upper right: seismic operational area in proximity to the Brazil/Malvinas Confluence zone (BMC) in the northern portion of the Argentine continental shelf. Lower right: seismic operational area east of Tierra del Fuego (TDF) in the southern section of the Argentine continental shelf. Points represent the location of floating marine debris sightings, and the polygons show the areas where seismic surveys were conducted by the seismic exploration vessel.

view ahead of the vessel. Sightings (considered as each time a FMD was observed) of FMD were performed by unaided eye, though 7 × 50 binoculars were used to verify item identification when necessary; sightings were immediately reported to the other operator to reduce sampling variability (Figure 2 A). Observations were conducted mostly in calm seas (measured in Beaufort scale, sea state ranging between 0 and 5) with 83.6% of the sampling days experiencing low swell (< 2 m) (both vessels combined). Still, no estimates were made on the distance between the FMD item and the observer. Reports of FMD included the type or category, abundance, and color of each item. Acknowledging the difficulties in comparing studies due to inconsistency of debris categorization (Blettler et al. 2017; Serra-Gonçalves et al. 2019, and references therein), for debris classification we adopted the most widely used methods. The categories included plastic, foamed plastic, paper, cloth, rubber, glass, metal, processed wood, and others (or non-classifiable debris), since they have been adopted by UNEP (Cheshire et al. 2009) and NOAA (Lippiatt et al. 2013). For each item, we further recorded several variables such as state (unbroken or fragmented), and presence/absence of biofouling (without taxonomical identification due to the distance and speed that the FMD passes through the monitored vessels). Based on their color debris were divided into white/clear, grey/silver, black, green, orange/brown, blue, red/pink, yellow and multicolour (> 3 colours) (Verlis et al. 2014). To facilitate comparison, the data on white and transparent light debris is presented separately. Additionally, the presumed sources of sighted FMD were classified into the following catego-

Table 1. Summary table based on the complete data set (2 cruises/81 days, 245 sightings of Floating Marine Debris (FMD) for seismic operational areas surveys Tierra del Fuego and Brazil/Malvinas Confluence zone.

	Tierra del Fuego	Brazil/Malvinas Confluence
Abbreviation	TDF	BMC
Ship	GECO VESPUCCI	GECO TRITON
Year	2012	2013
Sailing days	77	92
Date	29 September to 6 November	From 6 October to 31 December
Season	Spring	Spring
Geographical zone	Tierra del Fuego	Brazil/Malvinas Confluence zone
Km traveled	1,333.27	4,070.58
Total area covered (km^{-2})	11,398	2,000
Number of days surveyed (n)	38	87
Effective hours of observation	455:47	1,002:12
Numbers of days with presence of FMD	28	54
Total abundance of FMD	234	288
Percentage of FMD	74	62
Mean abundance of FMD	6.16 ± 8.84	3.31 ± 6.83
Density of FMD	0.17 items km^{-2}	0.07 items km^{-2}
Rate of FMD	12.3 items per hour of observation	6.9 items per hour of observation
Mean density of FMD	0.33 ± 0.65 items km^{-2}	0.08 ± 0.15 items km^{-2}
Speed of vessel (knots)	4.04 ± 0.31	4.19 ± 0.72

ries: construction' (bags of cement, beams, buckets of paint, etc.) (Figure 2 B), 'domestic' (food wrappings, disposable tableware, food packaging, shopping bags, and garbage bags) (Figure 2 C and 2 D), 'fisheries-related' (fish boxes, fishing nets, buoys, ropes, lines) (Figure 2 D), 'organic material' (wood, pine cones, leaves; not native to marine environments), and 'unknown debris' (items without a clear source were considered as derived from an unknown source). Plastic debris were further classified into single-use plastics (plastic bags, cutlery, straws, cups and food containers; the latter including non-wrapper food packaging, cartons, jugs, k-cups and drinking bottles) which are used once or only for a short time before being discarded (Schnurr et al. 2018; Simeonova and Chuturkova 2020).

During each sighting, we also recorded (from the ships' onboard sensors) the ships´ position, date, local time, and relative wind direction (in relation to the course of the vessel and measured in degrees) and its intensity (measured in knots). The speed of vessel was almost constant in each cruise (Table 1).

Data analysis

The percentage frequency of occurrence (FO%) of FMD was defined as the percentage of sightings in which each category of FMD was registered per day. The abundance of FMD was defined as the total number of each category of FMD tallied during each sighting. Densities of FMD were calculated by relating the total number of sighted items to the

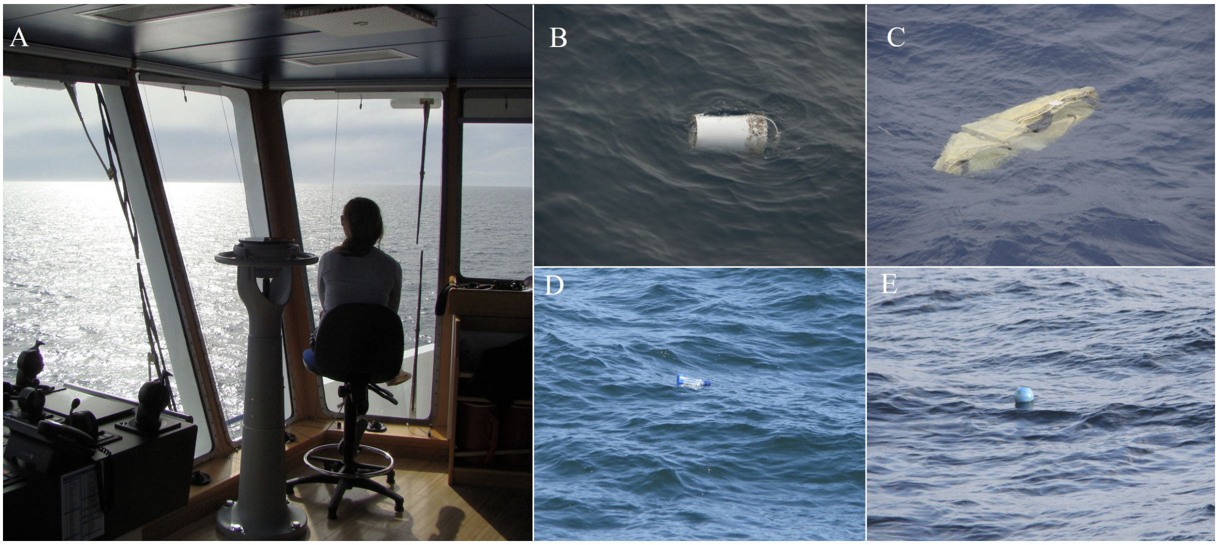

Figure 2. Observation point on the bridge of a seismic vessel (A). Examples of recorded floating marine debris according to their source: construction (e.g. paint bucket) (B), domestic (e.g. plastic bag and plastic bottle) (C and D), and fisheries-related (e.g. Buoy) (E) .

area surveyed during the observation. Thus, mean densities of FMD estimated for each ecosystem are expressed as number of items per km^{-2}. The 'Rate of Floating Marine Debris' refers to the measurement of the total number of floating marine debris items observed or encountered per unit of time, expressed as items per hour.

To analyze the data, we followed data exploration protocols as suggested by Zuur et al. (2010) and Zuur (2012). These protocols allowed us to identify outliers, assess data variability, examine relationships between covariates and the response variable, and evaluate collinearity between covariates. Initially, we employed a simple Generalized Linear Model (GLM) following Zuur's (2012) approach. Subsequently, we advanced to more complex models by incorporating smoothed variables using Generalized Additive Models (GAM) and accounting for excess zeros using Zero-Inflated models (ZIPs). Each ecosystem was modelled separately to explore the relationship between the rate of FMD and several explanatory variables including wind force (continuous variable), distance to the coast (continuous variable) and the interaction between both explanatory variables for each surveyed marine ecosystem separately. The best model was selected according to the Akaike criterion (Burnham and Anderson 2004).

Statistical analysis of the data was performed using R (v.4.2.3; R Core Team 2023), whereas maps were constructed using the ArcGIS10.1 program. In all cases, differences were considered significant where P was < 0.05. All reported values are means ($\pm$ SD), except where noted.

RESULTS

Floating marine debris were encountered on 74% and 62% of days surveyed in TDF and BMC ecosystems, respectively (Table 1). Overall, 522 FMD were counted during all sightings, with a mean abundance of 4.2 ± 7.6 items per sighting; a maximum of 51 FMD was recorded in one sighting. Average FMD density was estimated at 0.16 ± 0.39 items per km^{-2} (both sampled areas combined) (Table 1). Similar absolute abundance of FMD were encountered at both surveyed ecosystems, but their mean abundance varied significantly between ecosystems (Wilcox test W = 1263.5, $p = 0.032$) with higher loads in TDF (6.15 ± 8.84 items; maximum 38 items per sighting) when compared to BMC (3.31 ± 6.83; maximum 51 items per sighting). Likewise, densities and rate of FMD were significantly higher in TDF when compared to densities obtained in BMC (0.33 ± 0.65 versus 0.08 ± 0.15 items km^{-2}, Wilcox test W = 2097, $p = 0.015$; 7.0 ± 14.48 versus 12.48 ± 17.57 items per hour, Wilcox test W = 1248.5, $p = 0.027$) (Table 1).

The composition of FMD (as per the abundance parameter) at both ecosystems was dominated by plastic debris as an overall group (> 80%), followed by foamed plastics (Figure 3 A and B). Within plastic category, bags made up to 47.8% of plastic FMD, followed by other plastics like wrappers (12.7%), bottles (8.7%) (all considered single-used plastics), containers (5.9%), bottle labels (4.7%), and others (20.2%) irrespectively of the studied ecosystem (Figure 3 C). Unbroken plastic items (81%) were more abundant than fragmented items (both sampled ecosystems combined). The bulk of the plastic debris (98%) showed no signs of biofouling. According to its abundance, white/transparent (294 items, 56.4%), and multicolor (18.4%) debris prevailed, followed by a lesser proportion of yellow colored debris (5.6%) while the rest of the colour codes will not exceed a 5% occurrence rate (Figure 4). The main source of FMD –based on its abundance– included domestic activities (78.0%) (e.g. plastic bags, food wrappers, drinking bottles, food containers, among others), followed by fisheries-related (9.9%) (e.g. plastic cubes, ropes < 2 m in length, foamed plastic used in cold chambers, plastic buoys, among others) and construction (3.6%), with a less proportion of natural source (0.2%) regardless of the sampled marine ecosystem (Figure 3 D).

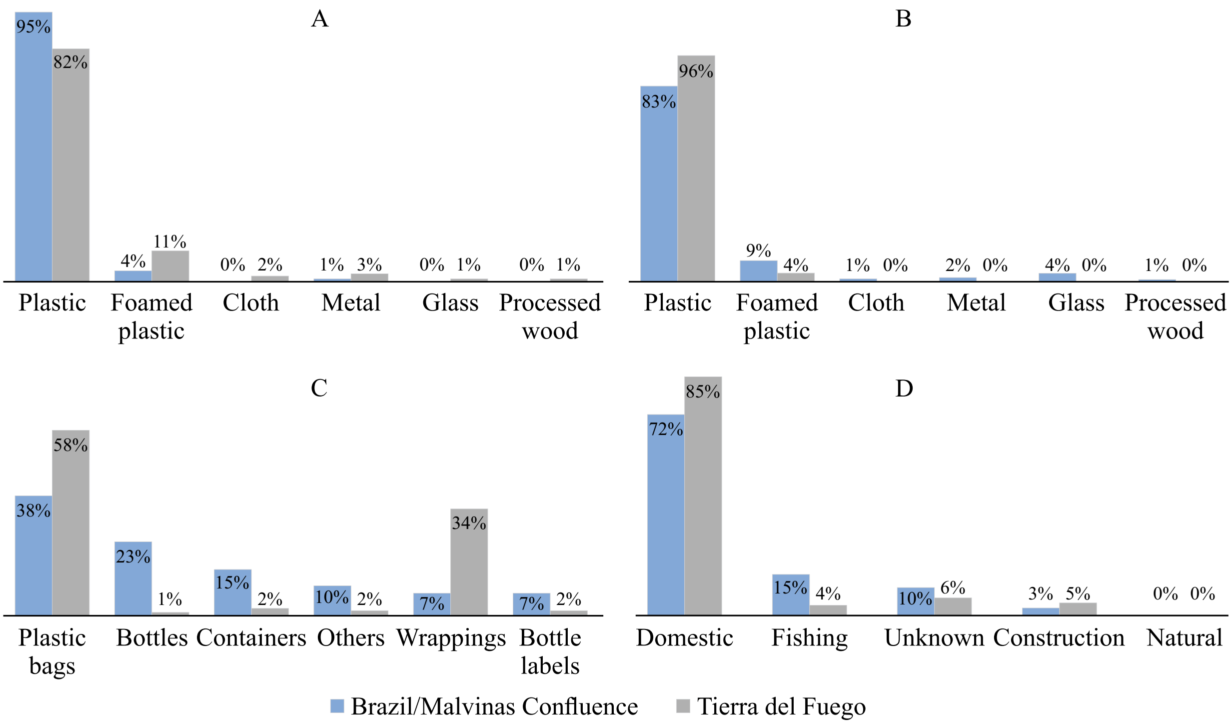

Figure 3. Frequency of occurrence (A); numeric abundance (B); plastic origin (C); and (D) source of FMD sighted aboard commercial seismic surveys performed in two marine ecosystems of the Argentine continental shelf.

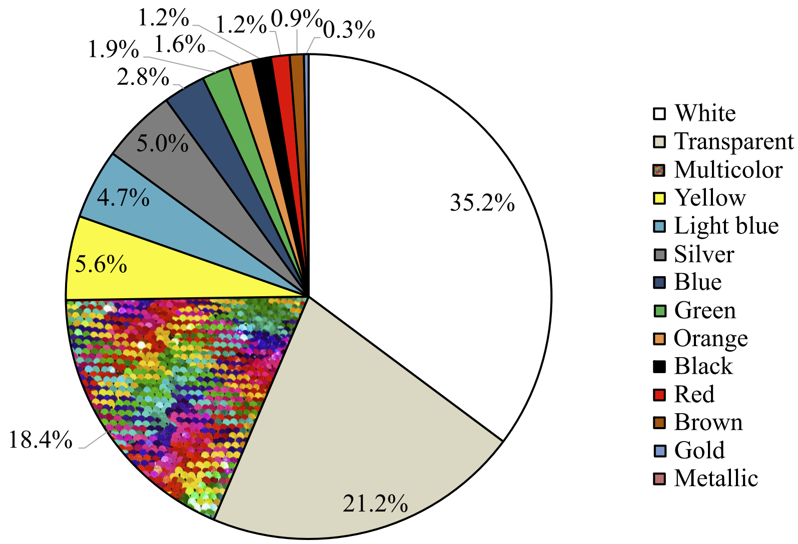

Figure 4. Percentage of FMD abundance sighted aboard two commercial seismic surveys in two marine ecosystems of the Argentine continental shelf categorized by color.

A statistically significant positive relationship between the rate of floating marine debris and proximity to a pollution source was found for TDF ecosystem. When the distance to the coast increases, the FMD rate also increases (estimate = 0.00032, $p = 0.03$) (Table 2).

On the other hand, for the deeper water ecosystem (BMC), the distance to the coast was no longer a factor affecting the amount of FMD; neither the distance to the coast nor the intensity of the wind force had a significant effect on the amount of FMD in this ecosystem (Table 2).

DISCUSSION

To our knowledge, the present study is the first to investigate the abundance and composition of floating marine debris at two contrasting pelagic ecosystems like the southern section of the Argentine continental shelf and the Brazil/Malvinas Confluence zone. Moreover, we present novel information regarding the categories and sources of FMD in both pelagic ecosystems. Our results indicated that the abundance and density of Floating Marine Debris (FMD) in the surveyed ecosystems were similar to those reported in other pelagic ecosystems of the southern Hemisphere. Previous studies have documented comparable levels of FMD in the SE Atlantic off South Africa (Morris 1980; Ryan 1988; Collins and Hermes 2019), the South Atlantic gyre (Ryan 2014; Ryan et al. 2019), and the SE Pacific off Chile (Thiel et al. 2003; Hinojosa and Thiel 2009), as well as in the wider south Pacific region (Gregory and Ryan 1997).

In this study, plastic debris outnumbered other debris categories when considering both ecosystems studied. This is in line with previous studies conducted regionally in other pelagic areas of the South Atlantic, including in South African waters (Ryan 2014) and in the South Atlantic gyre (Ryan et al. 2019) and elsewhere in the South Pacific off Chile (Thiel et al. 2003; Hinojosa and Thiel 2009). Furthermore, extensive evidence suggests that plastic debris is overwhelmingly prevalent in both terrestrial and marine environments on a global scale (Jambeck et al. 2015). In fact, between 50% and 80% of marine debris in the ocean is composed by plastics (Derraik 2002; Tourinho et al.

Table 2. Model summary for Floating Marine Debris (FMD) analysis in both surveyed ecosystems: Tierra del Fuego and Brazil/Malvinas Confluence zone.

Tierra del Fuego	AIC	BIC	logLik	deviance	df. resid
Family: gaussian (identity) Formula: RateFMD ~ 1 + NEAR_DIST Zero inflation: ~ 1 Dispersion estimate for gaussian family (sigma^2): 286	288.8	295.3	-140.4	280.8	34
	Estimate	Std. error	z value	Pr(>|z|)	
Conditional model					
(Intercept)	-4.8670906	10.4852218	-0.464	0.6425	
NEAR_DIST	0.0003208	0.0001489	2.154	0.0312	
Zero-inflation model					
(Intercept)	-1.0924	0.3865	-2.827	0.0047	

Brazil/Malvinas Confluence	AIC	BIC	logLik	deviance	df. resid
Family: gaussian (identity) Formula: RateFMD ~ 1 + NEAR_DIST + Wind_force Zero inflation: ~ 1 Dispersion estimate for gaussian family (sigma^2): 281	581.8	594.1	-285.9	571.8	82
	Estimate	Std. error	z value	Pr(>|z|)	
Conditional model					
(Intercept)	22.78	26.43	0.862	0.389	
NEAR_DIST	-3.756E-05	0.00008327	-0.451	0.652	
Wind_force	-0.4301	2.318	-0.186	0.853	
Zero-inflation model					
(Intercept)	-0.5446	0.2295	-2.373	0.0176	

2009). Thus, our results are in accordance with previous studies investigating FMD abundance and composition worldwide (e.g. Derraik 2002; Barnes et al. 2010; Lambert et al. 2020). The dominance of plastic FMD (also including non-floating plastic marine debris) is chiefly due to their high persistence and low density, high use by modern society, and increased production and commercialization through time (Sheavly and Register 2007). At the surveyed ecosystem scale, the terrestrial source of plastic debris, along with other types of debris, in close proximity to the eastern portion of Tierra del Fuego, includes the city of Rio Grande (population: 98,277 inhabitants, INDEC

2020). Additionally, the oilfields, pipelines, and gas treatment plants located at the southeastern portion of continental South America, both in Argentina and Chile (170 km north of Rio Grande), have also been identified as sources (Panza et al. 2015). Whereas the marine-based source of plastic FMD in the adjacent coastal space of this marine ecosystem encompasses chiefly fixed oil platforms at the very mouth of the Magellan Strait (Prefectura Naval Argentina, 2008) and the small-scale fishing fleets targeting benthonic resources with traps in near-shore waters of southern Santa Cruz Province (Perrotta et al. 2007). Although in the case of the BMC ecosystem, the terrestrial source of plastic debris may include, at some extent, urban areas settled in the La Plata River Basin like Buenos Aires and La Plata cities in Argentina and Montevideo in Uruguay concentrating about 12.2 million inhabitants (Censo 2022; Instituto Nacional de Estadística 2023). The marine-based source of plastic debris in the nearby coastal space of northern Patagonia, in close proximity to this ecosystem, involves the Argentinean and Uruguayan commercial fishing fleets. These fleets operate in a Common Fishing Zone that encompasses the Rio de la Plata and the adjacent marine area of 216,000 km^2 (Chaluleu 2003). Furthermore, the high-seas fishing fleets targeting tunas, regulated by the International Commission for the Conservation of Atlantic Tunas (ICCAT 2019), also contribute to this marine-based source. The main prevalent plastic FMD item sighted in this study had the shape of an unbroken debris. This strongly contrasts with the information available which indicates that plastic fragments smaller than 1 cm in diameter encompass the most abundant size class of marine debris in the open ocean (Cózar et al. 2014). However, macroscopic FMD in such matrix is often comprised of bottles, plastic bags, and Styrofoam (expanded polystyrene) that can be easily sighted at sea from ship surveys (Hinojosa and Thiel 2009; Depledge et al. 2013; Ryan 2014; Suaria and Aliani 2014; among others). In fact, the majority of the Floating Marine Debris (FMD) observed during surveys conducted along the entire Chilean coast in the South Pacific waters (Thiel et al. 2003) and along the route between Cape Town and Tristan da Cunha in the SE South Atlantic (Ryan 2014) consisted of unbroken plastic items. These items included plastic bags, bottles, tubs/cups, lids, lid-rings, and other forms of food packaging. Overall, this debris fall within the category of single-use plastics, which contribute to 60-95% of global marine plastic pollution (Schnurr et al. 2018). Besides the majority of sighted FMD ranged between 15-30 cm (Ryan 2014) or were smaller than 50 cm in diameter or length (Thiel et al. 2003); both types and sizes of FMD can be easily spotted from a vessel. It is known that low-density plastics, such as polypropylene and polyethylene, produce debris that is less dense than water and therefore likely to remain afloat (García Rellán et al. 2023).

In the present study, all color codes were registered for plastic FMD, with white/clear debris prevailing as the main color code. White-coded debris outnumbered clear-coded debris. According to Blettler et al. (2017), the variation in colour codes may be linked to the origin of plastics from different sources and to the intensive exposure (weathering process) of plastic debris. Regardless, FMD were not coloured coded in previous studies conducted in nearby pelagic ecosystems of southern South Pacific off Chile (Thiel et al. 2003; Hinojosa and Thiel 2009) or in pelagic waters around the Tristan da Cunha archipelago (Ryan et al. 2019). Still, regional comparisons are feasible as Ryan (2014) reported color-coded debris in a survey performed in waters of southeastern South Africa. In fact, he also found a greater proportion of white/clear color code category in FMD in such area. Thus, our results are in line with the few available literature for pelagic waters in the South Atlantic.

Domestic activities prevailed among the main presumed sources of FMD along both studied marine pelagic ecosystems. In spite of our results representing first-hand information on FMD sources in the target areas, this is an interesting finding at least for BMC, as the surveyed area is located some 250 km from the closest coastline off Argentina. The significant proportion of FMD originating from the presumed source reported in this study supports the hypothesis that a substantial amount of FMD in the Brazil/Malvinas Confluence zone results from land-based activities. These activities include urban areas and various industries located within the La Plata River Basin system. In fact, Acha et al. (2003) previously suggested the efficiency of this system as a trap for marine debris, particularly plastics. Additionally, the transport of FMD eastward by eddies in the western Argentine Basin, with diameters ranging from 50 to 350 km and averaging 150 km (Lentini et al. 2002), as well as the intense maritime traffic in this region, may contribute to this FMD presence. It is possible that a combination of both factors plays a role. The fact that nor wind or distant to the coast was significant in the rate of FMD suggests that other factors may be influencing the presence and distribution of FMD in the BMC area. Further research is needed to identify these additional factors and better understand the dynamics of FMD in deeper water ecosystems.

In this study, higher rates of FMD were found in the high seas east of Tierra del Fuego, indicating greater incidence in higher latitudes compared to the BMC area surveyed at lower latitudes. However, information from nearby pelagic marine ecosystems arrived to opposite results. For instance, Thiel et al. (2003) observed a latitudinal pattern in the South Pacific off Chile, with higher densities of FMD between 18° S and 40° S, and lower densities at higher latitudes (51° S), which are somewhat comparable to the latitudes of Tierra del Fuego (54° S-55° S). This difference in FMD density could be attributed to the proximity of TDF to the Isla Grande de Tierra del Fuego and the southeastern portion of continental South America, where urban settlements and terrestrial-based industries are located, in contrast to the more remote location of the BMC area in the high-seas of international domain (as shown in Figure 1). Moreover, the existence of urban settlements and oil platforms along the nearby coast further contributes to the significant amounts of FMD observed in TDF region. Another explanation for the observed differences could be the seasonal weakening of the northward flow of Sub Antarctic waters associated with Cape Horn and the Malvinas Current over the southern Patagonian Shelf, especially during the austral spring (Palma et al. 2008). This weakened flow may create a trapping effect for FMD in TDF area. Acquiring a comprehensive understanding of the quantity of marine debris is crucial for assessing its occurrence and impact on marine animals in our area (e.g. Campagna et al. 2007; Denuncio et al. 2011; Carman et al. 2015; Denuncio et al. 2017; Mandiola et al. 2021; Prosdocimi et al. 2021; Seco Pon et al. 2023; Padula et al 2023). Moreover, information regarding the presence of FMD in waters of Argentina are equally important for assessing the health of the ecosystem and further possible impacts of plastic debris –particularly microplastics– in marine food webs, including species of commercial interest (Mandiola et al. 2021), and also for public safety as debris may turn into navigational hazards to fishing and sailing vessels as well as to maritime traffic (Hong et al. 2017).

Various types of vessels, including seismic vessels, play a vital role in documenting the presence of FMD in both coastal and pelagic waters, particularly during oil and gas exploration activities. This study highlights the significant role of seismic vessels as platforms for monitoring FMD in the Argentine continental shelf and adjacent waters, providing a valuable baseline for future researchers and managers to assess temporal changes in FMD abundance or composition in the area. Understanding the dynamics of FMD and its potential impact on marine ecosystems is crucial for effective conservation and management efforts. The information presented in this study may contribute to the implementation of actions framed in the Sea Turtles, Seabirds, and Marine Mammals Argentine National Plans of Action and related conservation actions agreed within the frames of the Inter-American Sea Turtle Convention, the Agreement on the Conservation of Albatrosses and Petrels, and the International Whaling Commission (IWC) –all international instruments that Argentina ratified in 2010, 2006 and 2011 respectively. These results may also feed decision makers and administration agencies to develop and better implement regulations including the ecosystem approach to fishery management, as well as management plans for the exploration and exploitation of non-renewable resources.

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