Rapid increase in Asian bottles in the South Atlantic Ocean indicates major debris inputs from ships

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Most plastic debris floating at sea is thought to come from land-based sources, but there is little direct evidence to support this assumption. Since 1984, stranded debris has been recorded along the west coast of Inaccessible Island, a remote, uninhabited island in the central South Atlantic Ocean that has a very high macrodebris load (~5 kg·m^{-1}). Plastic drink bottles show the fastest growth rate, increasing at 15% per year compared with 7% per year for other debris types. In 2018, we examined 2,580 plastic bottles and other containers (one-third of all debris items) that had accumulated on the coast, and a further 174 bottles that washed ashore during regular monitoring over the course of 72 d (equivalent to 800 bottles·km^{-1}·y^{-1}). The oldest container was a high-density polyethylene canister made in 1971, but most were polyethylene terephthalate drink bottles of recent manufacture. Of the bottles that washed up during our survey, 90% were date-stamped within 2 y of stranding. In the 1980s, two-thirds of bottles derived from South America, carried 3,000 km by the west wind drift. By 2009, Asia had surpassed South America as the major source of bottles, and by 2018, Asian bottles comprised 73% of accumulated and 83% of newly arrived bottles, with most made in China. The rapid growth in Asian debris, mainly from China, coupled with the recent manufacture of these items, indicates that ships are responsible for most of the bottles floating in the central South Atlantic Ocean, in contravention of International Convention for the Prevention of Pollution from Ships regulations.

plastic pollution | China | Tristan da Cunha | South America | MARPOL Annex V

Plastic pollution is a pressing environmental concern (1) that has attracted the attention of researchers, policy makers, and the general public. The United Nations' Sustainable Development Goals include the density of floating plastic as a key indicator of ocean pollution under Sustainable Development Goal 14.1 (https://www.un.org/sustainabledevelopment/). Global production of plastics has increased rapidly during the last 70 y, to more than 300 million tons per year, and continues to grow at around 8% per year (2). Most waste plastic is either dumped in landfills or released into the environment (2). Because plastics are relatively light, with densities similar to that of water, it disperses far from source areas, and plastics are now ubiquitous in the world's oceans (1).

Oceanographic models and empirical observations of debris at sea both indicate that debris floating at the ocean surface tends to accumulate in the center of ocean gyres in so-called garbage patches (3–5). As a result, the shores of oceanic islands close to these zones often suffer exceptionally high levels of plastic pollution, despite being located far from major source areas for plastic waste (6–9). The accumulation of plastic on remote island shores is a useful tool to monitor marine plastics (8), but the origins of most plastic items washing ashore are hard to infer, because they are too small to attribute to specific sources based on manufacturers' marks or functional attributes.

Understanding the sources of marine debris is an essential precursor to mitigation of the problem. It is widely assumed that roughly 80% of debris floating at sea derives from land-based sources (10), especially since 1989, when the dumping of plastics into the sea was banned by Annex V of the International Convention for the Prevention of Pollution from Ships (MARPOL). However, there is little robust evidence to support this estimate, particularly for oceanic regions. Some studies have shown a decrease in debris at remote sites since MARPOL V came into force (11), but other studies have reported continued stranding of debris from distant countries, which typically is attributed to shipping (12, 13). Much of the debris stranding at islands in the Atlantic Ocean is fishery-related (7), and Lebreton et al. (14) concluded that marine inputs accounted for a higher proportion of floating debris in the North Pacific garbage patch than expected from models of marine debris sources.

Even among macrodebris items, it can be difficult to determine the origins of stranded debris (15). Although some waste categories are readily ascribed to offshore activities (fishing gear, ropes, boat fenders, outboard motor oil bottles, etc.), it is hard to infer the origin of waste categories such as packaging for food, drinks, and domestic goods (cleaning and sanitary products), which could derive from either ships or land-based sources (15, 16). Plastic bottles are a useful tracer of such debris because they often have labels or other distinctive features that indicate their country of manufacture (13, 14). Many bottles also are date stamped (14), providing an estimate of the maximum time they have had to disperse at sea. These durations can be used to assess the likely origin based on models of ocean surface drift.

We use bottles stranding at Inaccessible Island, an uninhabited island in the Tristan da Cunha archipelago, central South Atlantic Ocean (Fig. 1), to infer the main source of debris in the South

Significance

Many oceanic islands suffer high levels of stranded debris, particularly those near subtropical gyres where floating debris accumulates. During the last 3 decades, plastic drink bottles have shown the fastest growth rate of all debris types on remote Inaccessible Island. During the 1980s, most bottles drifted to the island from South America, carried 3,000 km by the west wind drift. Currently, 75% of bottles are from Asia, with most from China. The recent manufacture dates indicate that few bottles could have drifted from Asia, and presumably are dumped from ships, in contravention of International Convention for the Prevention of Pollution from Ships regulations. Our results question the widely held assumption that most plastic debris at sea comes from land-based sources.

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Atlantic garbage patch (17). We report the rapid increase in Asian bottles stranding at this island during the last 2 decades, and use their stamped dates to show that most of these items come from vessels operating in the region.

Results

After surveys in the 1980s, we recorded 3,515 debris items along 1.1 km of the west coast of Inaccessible Island in 2009 and 7,368 items weighing 5 tons in 2018. Over the course of 72 d, a further 239 debris items washed ashore and 477 items were exhumed. This represents 7.3 macrodebris items weighing ∼5 $kg \cdot m^{-1}$, because of the many large debris items from fisheries (floats, fish trays) and shipping-related activities (ship's hawsers, buffers, etc.). This is among the highest levels recorded at an oceanic island globally (7, 9), despite the paucity of small items (<2 cm) recovered because they disappear into crevices between the cobbles and boulders.

Bottles and other single-use containers (including aerosols, food jars, etc.), hereafter referred to as bottles, were the most abundant type of debris in both 2009 (29.2% of all debris items) and 2018 (34.1%). The growth rate of this litter category (10.7% per year since 1984; $r^2 = 0.997$; *SI Appendix*, Fig. S1) was faster than that for all other debris items combined (7.1% per year; $r^2 = 0.965$). In 2018, bottles were more abundant in newly arrived debris (72.8%) than accumulated surface debris (34.1%) or exhumed debris (13.8%; $\chi^2 = 246.6$; df = 2; $P < 0.001$).

Most bottles in 2018 were plastic (97.8%), with only 1.6% metal (mostly aerosols) and 0.6% glass. However, glass bottles might be underrepresented as a result of breakage, given the strong wave action and rugged shoreline (glass bottles = 2.3% of newly arrived bottles compared with 0.5% of accumulated bottles; $\chi^2 = 5.88$; df = 1; $P < 0.01$). Almost all plastic bottles were made from polyethylene terephthalate (PET; 87.0%) or high-density polyethylene (HDPE; 12.8%), with only 0.2% polypropylene (PP). A much greater proportion of PET bottles had lids (80.3%; $n = 2{,}223$) than HDPE or PP bottles (30.9%; $n = 331$; $\chi^2 = 362.0$; df = 1; $P < 0.001$), presumably because PET is more dense than seawater. Indeed, among newly arrived items, all PET bottles ($n = 150$) had lids compared with only 39% of bottles made from HDPE and PP ($n = 18$; $\chi^2 = 88.3$; df = 1; $P < 0.001$), polymers with densities less than seawater. Most PET bottles lacking lids were old and battered, and probably lost their lids after stranding, either through mechanical damage (Fig. 2*B*) or UV degradation (Fig. 2*C*).

The contents of most bottles could be determined, with drink bottles predominating. PET drink bottles had the fastest growth rate among all debris items since 1984, increasing at 14.7% per year ($r^2 = 0.995$). As a result, they were more abundant among newly arrived bottles (85.1%) than among accumulated bottles (77.4%; $\chi^2 = 5.11$; df = 1; $P = 0.014$; Table 1). Almost all drink bottles that could be identified were for either water or soft drinks, with only 0.6% for alcoholic beverages. Water bottles comprised at least 61% of drink bottles overall, and also were disproportionately represented in newly arrived debris (71%; $\chi^2 = 6.61$; df = 1; $P = 0.006$). Other common bottle types were used for a variety of domestic and general use products (e.g., PET bottles for cooking oil, sauces, other food products, and detergents; HDPE bottles for shampoo and liquid soaps, detergents and other cleaning products, sauces, pills, motor oil, etc.).

The stamped date was determined for 478 bottles examined in 2018 (17% of all bottles, but 57% of newly arrived bottles). The oldest debris item found was the bottom of a large HDPE canister made in March 1971 (Fig. 2*D*), but most items were of recent manufacture (Fig. 3). The modal age was 1 to 2 y for both newly arrived ($n = 99$) and accumulated bottles ($n = 379$), but on average, newly arrived bottles were made more recently (mean ± SD stamped date, 1.26 ± 0.62 y; median, 1.1 y) than accumulated bottles (mean ± SD stamped date, 3.7 ± 4.7 y; median, 2.2 y; t = 8.98; $P < 0.001$). Most newly arrived bottles (90%) had date stamps within 2 y of washing ashore. PET bottles typically were younger compared with those made from other materials (Fig. 3), both for newly arrived (mean ± SD stamped date, 1.18 ± 0.42 y [median, 1.1 y] compared with mean ± SD stamped date, 2.45 ± 1.56 y [median, 2.3 y]; t = 7.26; $P < 0.001$) and accumulated (mean ± SD stamped date, 2.75 ± 2.39 y [median, 2.0 y] compared with mean ± SD stamped date, 12.07 ± 9.32 y [median, 9.7 y]; t = 71.52; $P < 0.001$) items.

Goose barnacles and bryozoans were found much more often on newly arrived bottles (51%) than on accumulated bottles (2%). There was a tendency for a lower proportion of recently manufactured bottles to be fouled (38% of bottles <1 y compared with 50% of bottles >1 y) but this effect was not statistically significant ($\chi^2 = 1.35$; df = 1; $P = 0.175$). Barnacles tended to be most prevalent on bottles that contained some water, and thus did not have excessive windage. Some bottles carried substantial loads of goose barnacles; for example, a 45 g plastic 2-L water bottle weighed 580 g (wet weight) before the barnacles were removed.

The country or region of origin of bottles was determined for 40% of bottles (71% of new arrivals), which came from 35 countries (Fig. 4 and *SI Appendix*, Table S1). In the 1980s, two-thirds of bottles derived from South America (Fig. 5). By 2009, Asia just passed South America as the major source of bottles (Fig. 5), and by 2018, Asian bottles made up 75% of all bottles (Table 1). The proportion of Asian bottles was higher among newly arrived

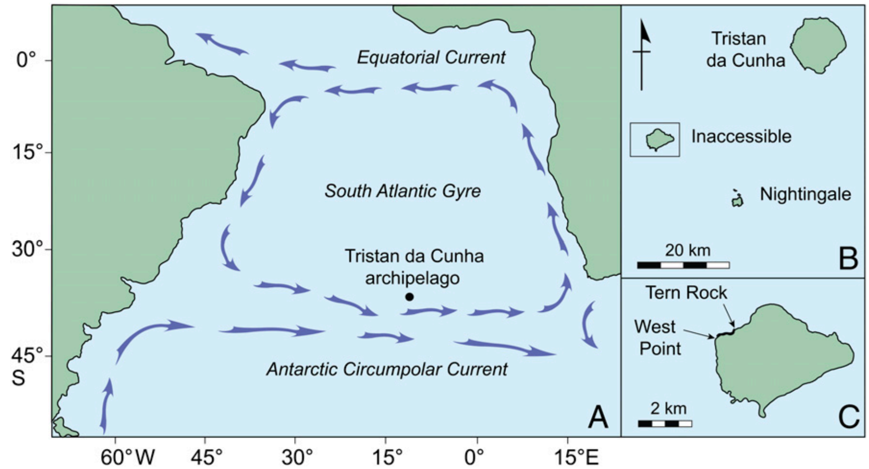

Fig. 1. (*A*) The location of the Tristan da Cunha in the central South Atlantic Ocean in relation to the major surface currents. (*B*) The Tristan archipelago. (*C*) The location of the study area at Inaccessible Island.

Fig. 2. (*A*) Checking cached bottles for manufacturers' marks on Inaccessible Island. (*B*) Mechanical wear on Master Kong 500 mL water bottles over the course of roughly 3 y. (*C*) A soft drink bottle with a stamped date of April 2011 showing UV damage to the HDPE lid. (*D*) The date stamp on the oldest item found, an HDPE canister made in March 1971. (*E*) A 20-L canister manufactured in November 1990 showing surface crazing and embrittlement characteristic of UV degradation.

bottles than among accumulated bottles (Table 1; $\chi^2 = 4.72$; df = 1; $P = 0.017$). This was mainly due to drink bottles, which made up a much greater proportion of Asian bottles than those from other regions (Table 1; $\chi^2 = 79.5$; df = 1; $P < 0.001$). Among newly arrived bottles, the stamped date of Asian bottles (mean ± SD stamped date, 1.26 ± 0.40 y; n = 75) averaged less than that of South American bottles (mean ± SD stamped date, 1.74 ± 1.69 y; n = 9), but the difference was not significant (t = 0.690; $P = 0.246$). Manufacturers responsible for most bottles included 2 large multinational beverage companies, 5 Chinese companies and 2 Argentinian producers of bottled water (Table 2). Half of all bottles came from China (Table 1), a country from which no bottles had been recorded in previous visits in the 1980s and 2009.

Discussion

An estimated 480 billion plastic drink bottles are produced each year globally (18), many of which are not disposed of appropriately, making them ubiquitous pollutants. A recent review

Table 1. The regions of origin of bottles and other plastic containers stranded on Inaccessible Island in 2018, contrasting accumulated bottles and those that arrived during our study, and drink bottles with all bottles and containers

	Newly arrived (n = 123), %	Accumulated (n = 970), %	Drink (n = 952), %	All bottles (n = 1,093), %
Asia	82.9	73.4	79.3	74.5
China	59.3	49.5	57.5	50.6
South America	13.8	20.9	16.3	20.1
Africa	2.5	2.5	2.4	2.5
Europe	0.8	2.3	1.6	2.1
North America	0.0	0.8	0.4	0.7
Australasia	0.0	0.1	0.0	0.1

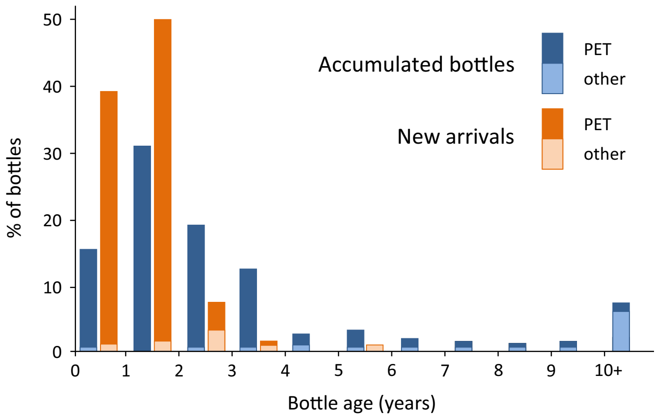

Fig. 3. The marked ages of bottles and other containers stranded on Inaccessible Island in 2018, contrasting accumulated debris (standing stock) and newly arrived bottles, and divided into PET bottles (n = 430) and bottles made with other materials (n = 42 HDPE, 3 PP, 2 glass, 1 metal).

found bottles to be the most common type of macrodebris in European rivers (19). Sealed bottles disperse well because they are highly buoyant and thus not prone to sinking through biofouling (20). As a result, the proportion of bottles among floating debris increases from coastal to oceanic waters (17). Because many bottles bear marks that indicate both the country and date of manufacture, they are a valuable tool to infer debris sources, especially from distant regions (13).

Numerous websites report that plastic bottles last 450 y in the environment, but this estimate is necessarily based on a broad extrapolation. Although 1 heavy-duty HDPE canister was close to 50 y old (Fig. 2*D*), another similar canister showed severe UV damage within 30 y (Fig. 2*E*), and PET bottles degrade even more rapidly, confirming the mechanical damage caused by cobble beaches in areas with high wave action (21). The thin-walled PET bottles used for still water degrade within a few years in this high-energy environment (Fig. 2*B*), whereas at least some PET bottles for carbonated drinks persist for longer, sometimes outlasting their HDPE lids (Fig. 2*C*). Our maximum age estimates for PET bottles doubtless are influenced by the loss of date-stamps as they degrade; the oldest date stamped PET bottle was just older than 20 y. Engraved dates last much longer than printed dates.

Barnes et al. (22) highlighted the rapid growth in plastic debris at remote islands and seamounts in the Atlantic Ocean, but did not estimate how growth rates differ among types of debris. The numbers of drink bottles at Inaccessible Island have increased at more than twice the rate of nonbottle debris during the last 3 decades. This largely reflects the 8.5% per year growth in the bottled water industry, which is projected to be worth US$280 billion by 2020 (https://www.marketresearchstore.com/report/bottled-water-market-z39681). This rapid growth partly explains why the proportion of bottles among newly arrived debris was roughly double that among accumulated debris. However, 2 other factors could contribute to this large disparity. There is probably more rapid turnover on the beach for bottles than for many other debris items; for example, we found PET bottles blown by the wind up to 50 m into the tussock grass that backs the study area. Also, items such as fish trays and blocks of polystyrene break up in the high-energy beach environment, resulting in an increase in the number of items in these categories with time after stranding (unlike bottles, which tend to remain more or less intact). Such factors need to be considered when interpreting differences in numerical debris composition between accumulated and newly arrived items on beaches.

Barnes et al. (22) also did not determine the source of the debris threatening remote Atlantic Ocean marine ecosystems, although Monteiro et al. (7) concluded that much of the debris came from offshore sources. There is no doubt that some floating debris travels long distances across ocean basins (e.g., refs. 14, 23, and 24). Indeed, Tristan da Cunha provides a good example of this, with debris from South America, 3,000 km upwind, predominating on Inaccessible and other islands in the archipelago in the 1980s (25, 26). The surface drifter model, PlasticAdrift, shows how floating debris in coastal waters off the densely populated east coast of South America between 20 °S and 40 °S disperses eastward in the west wind drift, reaching Tristan in 1 to 2 y. This accords well with the ages of bottles from South America that washed ashore during our survey, although sealed bottles, being highly buoyant, might move considerably faster than surface drift models predict due to their windage (27, 28). However, it is important to note that the ages of bottles reported here are only approximate; the lag between manufacture and use tends to overestimate the time between dumping and stranding, whereas the possible inclusion of some best before dates will tend to underestimate the actual age.

PlasticAdrift suggests that floating debris from the west coast of southern Africa also should be entrained in the South Atlantic gyre, and that debris from the south and east coasts of South Africa has a reasonable chance of entering the Atlantic via the Agulhas Current. Once in the South Atlantic gyre, floating debris

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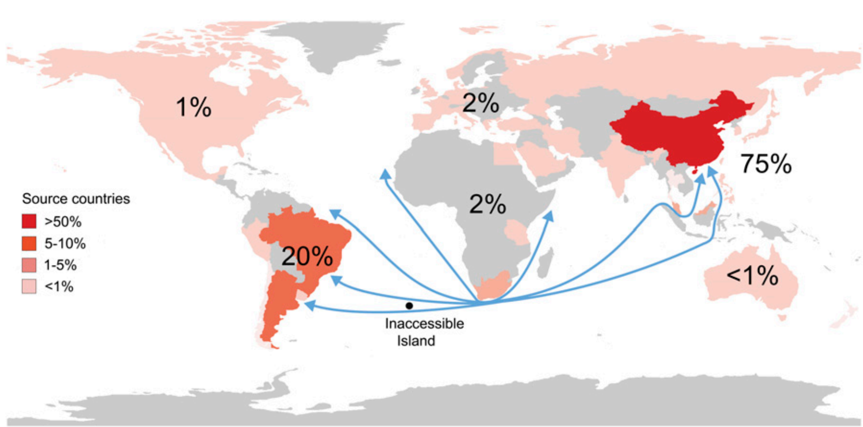

Fig. 4. The countries where bottles found on Inaccessible Island in 2018 were manufactured, showing the major shipping routes around the Cape. The percentages on the map reflect the contribution per continent.

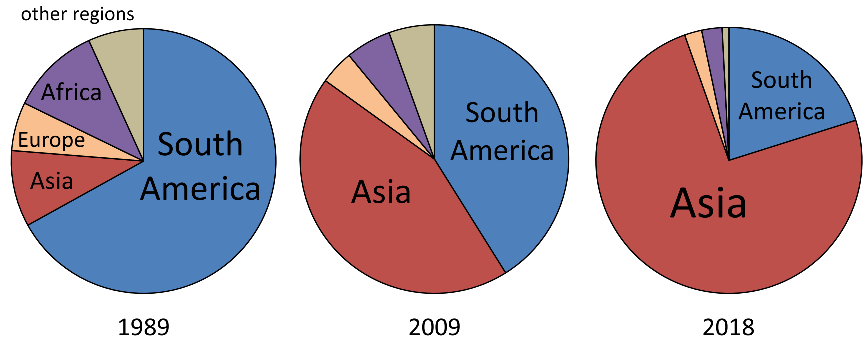

Fig. 5. Trends in the origins (region of manufacture) of bottles and other containers stranded on Inaccessible Island from 1989 to 2018.

typically is retained for at least 10 y (http://plasticadrift.org/). This should see a large amount of African debris reaching Inaccessible Island shores, given that South Africa is estimated to be the 11th worst global offender for land-based inputs of plastic waste into the oceans, more than any South American nation (Brazil, ranked as 16th globally, is the only South American country in the top 20 nations; ref. 29). South Africa accounted for 11% of the bottles on Inaccessible Island in 1989, but many probably came from the 2 vessels conducting the local rock lobster fishery at the time. These vessels operate from Cape Town, and most of their supplies come from South Africa. In the 1980s, before MARPOL Annex V came into force, much of the fishing vessels' general waste was dumped at sea around the islands. This has since improved considerably, with little waste washing ashore from the fishery. Although there has been an increase in the number of bottles made in South Africa during the last 3 decades, the proportion of bottles from African countries has decreased steadily, going from 11% in 1989 to 5% in 2009 and to only 2% in 2018, given the much faster increase in bottles mainly from Asia (Figs. 4 and 5).

South America has been the primary source of the fishing gear on Inaccessible Island since the 1980s, with the proportion of Asian gear, if anything, decreasing during the last 3 decades (*SI Appendix*, Table S2). This invites the question: Why has there been such a marked increase in the proportion of Asian bottles in the last decade? Bottles are classed as general or mixed-source items because they could derive from ships or land-based sources (15). However, by identifying the place and approximate date of manufacture, we can make strong inferences about the origins of bottles manufactured in distant countries or regions of the world (13). For Asian debris, PlasticAdrift suggests that a small proportion of the bottles originating from India and Southeast Asian countries might reach the South Atlantic from the Indian Ocean via the Agulhas Current, but this will take 3 to 5 y. Debris originating from China, Taiwan, Japan, and Korea is mostly entrained into the North Pacific, with very little chance of drifting to the South Atlantic.

Of course, some bottles might be exported to be sold (and disposed of) away from the country of manufacture (30). China is the second largest exporter of water globally, but little if any water is imported to South America or Africa (http://www.grida.no/resources/5852), the 2 continental source regions closest to Inaccessible Island. Virtually all bottled water and soft drinks for sale in these regions are manufactured locally. Given the fact that drifting from Asia within a few years is highly unlikely, we conclude that shipping is the most likely source of the recent increase in Asian bottles, especially the dominance of Chinese bottles during the last decade. Several other results support this conclusion. First, newly arrived Asian bottles were, if anything, manufactured more recently than bottles from other source areas (principally South America); this should not be the case if they had drifted from their country of origin. Second, the tendency for goose barnacles to be less common on newly manufactured bottles than older bottles suggests that such items have not been at sea for very long, consistent with them being dumped from ships. Finally, the top 3 manufacturers of bottles reaching Inaccessible Island (Table 2) are the same as those responsible for foreign-sourced bottles stranding on the east coast of Australia, which probably derive from ships (13).

Some bottles may come from the large Asian fishing fleet in the South Atlantic; fishery observers report frequent illegal dumping of plastics from fishing vessels (e.g., refs. 31 and 32). However, the Asian high seas fleet has operated in the South Atlantic Ocean at a similar level of effort since the 1990s (33), which does not explain the rapid increase in bottles during the last decade (although there might have been a switch to using more bottled water). The recent dominance of Chinese bottles also does not fit with debris coming from fishing vessels, because most fishing effort in the region is by Taiwan and Japan (33). Merchant shipping probably is responsible for much of the recent increase in especially Chinese bottles (13). Merchant

Table 2. The major producers of drink bottles stranded on Inaccessible Island in 2018 (all manufacturers responsible for at least 10 bottles)

Manufacturer	Country	Newly arrived	Accumulated	Total
The Coca-Cola Company*	Multinational	23	197	220
Tingyi/Master Kong	China	45	102	147
Nongfu Spring	China	6	126	132
Hangzhou Wahaha Group	China	10	80	90
Ice Dew (Coca-Cola)	China	7	16	23
PepsiCo	Multinational	2	20	22
Sierra de los Padres	Argentina	1	19	20
Villavicencio	Argentina	0	19	19
KSF Ice Tea	China	0	10	10

*Coke, Sprite, Fanta, Schweppes, etc.

ship traffic globally increased 4-fold from 1992 to 2012 (34), and there is an increasingly busy shipping lane from South America to Asia, principally China (35, 36). In 2016, more than 2,400 cargo vessels passed Tristan, for an average of 6.6 per day (37). Urgent action is needed to reduce illegal dumping by all vessels, which is in contravention of MARPOL Annex V. Producers of products that frequently are littered (Table 2) also need to take greater responsibility for the downstream effects of their packaging (38).

Study Area and Methods

Inaccessible Island is 1 of 3 islands in the Tristan da Cunha archipelago, central South Atlantic Ocean (Fig. 1). It is uninhabited and is visited only occasionally (at most 1 to 2 landings per year). Visitors sometimes collect a few floats and intact fishing trays, but most stranded debris is left to accumulate.

The amounts, composition, and origins of anthropogenic debris found along 1.1 km of cobble and boulder shoreline on the island's exposed west coast (*SI Appendix*) was reported in the 1980s (25, 26, 39). The standing stock of debris was again recorded in October 2009 and September to November 2018. Items were left in situ in 2009, but were collected on September 15 to 16, 2018 (Fig. 3*A*). From September 16 to November 26, 2018, the study area was searched for newly stranded debris on 55 d. Items were identified and grouped by function (fishing gear, packaging, etc.) and type of material (plastic, glass, metal, etc.), although this article focuses on bottles and other containers. The presence of epibionts was recorded, and we scored whether bottles and other containers were sealed with a lid. Manufacturers' marks were used to identify the country/region of origin and date stamps (*SI Appendix*).

We fitted exponential growth models to estimate the growth rates in the number of debris items. χ^2 goodness-of-fit tests were used to assess differences in proportions of debris types or sources, with Yates' correction for continuity where appropriate. Mann–Whitney *U* tests (using the normal approximation for large sample sizes) were used to compare the ages of bottles because the distribution of ages was not normally distributed. The likely drift paths and dispersal rates of floating bottles was inferred from a model based on observed drifter tracks (ref. 4 and http://plasticadrift.org/).

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