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ABSTRACT

Baseline measurements were made of the amount and weight of beached marine debris on Sand Island, Midway Atoll, June 2008–July 2010. On 23 surveys, 32,696 total debris objects (identifiable items and pieces) were collected; total weight was 740.4 kg. Seventy-two percent of the total was pieces; 91% of the pieces were made of plastic materials. Pieces were composed primarily of polyethylene and polypropylene. Identifiable items were 28% of the total; 88% of the identifiable items were in the fishing/aquaculture/shipping-related and beverage/household products-related categories. Identifiable items were lowest during April–August, while pieces were at their lowest during June–August. Sites facing the North Pacific Gyre received the most debris and proportionately more pieces. More debris tended to be found on Sand Island when the Subtropical Convergence Zone was closer to the Atoll. This information can be used for potential mitigation and to understand the impacts of large-scale events such as the 2011 Japanese tsunami.

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Marine debris is one of the important management problems facing the islands in the Papahānaumokuākea Marine National Monument (Monument) (Selkoe et al., 2008). The coastal areas of these islands are dynamic environments in which debris is deposited on the beaches and re-circulated into the near-shore area via wave action, tides, and storms. Because of the minimal human population in the Monument and rigorous on-island waste management, marine debris comes entirely from sources external to the Monument. Marine debris research in the Monument has focused on the impact of fishing nets on coral systems and the endangered Hawaiian monk seal (*Monachus schauinslandi*) (Boland and Donohue, 2003; Dameron et al., 2007). This has resulted in marine debris management being focused on removal of fishing nets and other gear. Little is known about other beached marine debris in the Monument (McDermid and McMullen, 2004; Morishige et al., 2007), other than that debris deposited on Monument beaches arrives from non-Monument sources. The objective of this study was to collect baseline information on the full spectrum of marine debris deposited on Monument beaches.

The study was done on Sand Island, Midway Atoll; Sand Island is part of the Midway Atoll National Wildlife Refuge. The island has an average population of 92 people and has the infrastructure to support a monitoring program. Four monitoring sites were used; the sites were 150-m lengths of beach with randomly chosen starting points. Two sites were on North Sand Island (facing the North Pacific Gyre), one site was on the west side (oblique to the Gyre), and one was on the south side (where the fringing reef is closest to shore) (Fig. 1). Site boundaries were established using GPS and marked at ground level so as not to pose a hazard to flying birds or other wildlife using these beach areas. The markers were made from existing debris found on the island – derelict fishing buoys anchored into the sand by construction rebar and ropes.

Surveys were done June 2008–July 2010 by volunteers stationed on the Refuge for 3 month stints. Field sampling protocol followed that of the National Marine Debris Monitoring Program (Ribic et al., 2010). All sites were cleaned 30 days prior to the start of data collection. Then surveys were conducted 28–32 days from the previous survey date. The range of days was needed to accommodate the possibility of protected wildlife (e.g., Hawaiian monk seals) occupying an area of the survey plot; the survey was delayed if a protected species was present. Surveys were conducted as near to low tide as possible. The volunteers had been trained in the survey technique and had photo guides of debris items to assist in identification. Twenty-three surveys were completed.

On each survey, volunteers collected all marine debris larger than 2.5 cm in length, height, width or diameter found on the site from the water's edge up to the berm, vegetation or dune area (Ribic et al., 2010). Only debris resulting from the US Navy's previous occupation of Midway (e.g., metal wire, concrete pieces) was not collected. Debris fragments, even if recognizable as part of an item,

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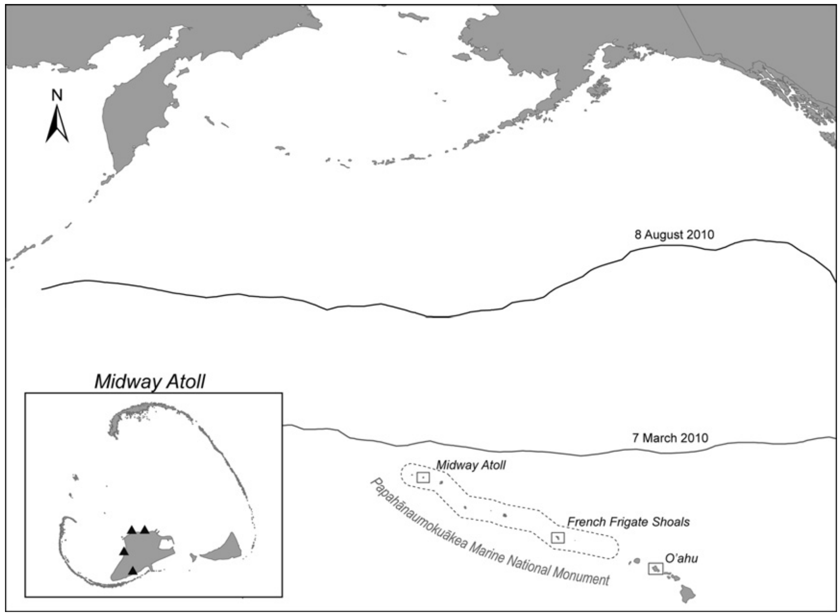

Fig. 1. Midway Atoll and the location of the Subtropical Convergence Zone, represented by the 18 °C isotherm line, at two time periods (solid lines with dates). Survey sites on Sand Island, Midway Atoll, are indicated by triangles.

were classified as miscellaneous pieces unless the fragment represented 50% or more of the recognizable item. If a collection of recognizable debris fragments formed 50% of a known item, this collection of debris was recorded as one item in its appropriate descriptive category. All debris was cleaned of sand, bagged, and removed from the site. A final walk-through was done to ensure that all debris present on the beach surface was collected. Debris was categorized into pieces and identifiable items and weighed (kg) separately. Seventy-one pieces were randomly selected to determine their polymer composition; the samples were rinsed with plain water, dried and then stored in plastic bags for shipment to a laboratory.

For statistical analysis, all identifiable items were put into the following categories: fishing/aquaculture/shipping-related, plastic bags, beverage/household products-related, food containers, toys/sport equipment, smoking-related, medical/health/personal items, appliances/equipment, construction material, and automotive parts. Debris pieces were categorized as plastic, foamed plastic, glass, metal, or rubber. Compositional analysis of the pieces was done by the Analytical Sciences Division of The Dow Chemical Company, Midland, MI. All pieces were analyzed using Fourier Transform Infrared (FT-IR) spectrophotometry. Two of the pieces were further analyzed by pyrolysis–gas chromatography–mass spectrometry to confirm results of the FT-IR (which were confirmed). The polymers of interest were those used to make the common items found on beach surveys, specifically nylons (fishing line, nets), polyesters (water/soda bottles, fabrics), polypropylenes (ropes, food/personal care packaging, automotive components, caps and cups), polycarbonates (automotive components, eyewear lenses, electronics, DVDs/CDs), polystyrenes (cutlery, cups, food/protective packaging, insulation), and polyethylenes (food packaging, detergent bottles, pipes/tubing, refuse/storage bins, buckets and bags). The samples were classified according to the major polymer present (e.g., polyethylene samples containing a small amount of polypropylene were categorized as polyethylene).

The 18 °C SST isotherm can be used as an index to how close the Subtropical Convergence Zone, which concentrates debris, is to the Atoll (Pichel et al., 2007). Sea surface temperature (SST) data were obtained from the optimum interpolation SST analysis V2 (Reynolds et al., 2002). Weekly SSTs were downloaded from NOAA Earth System Research Laboratory Physical Sciences Division, (2011) in a one-degree grid and loaded into ArcMap (Environmental Systems Resource Institute, 2009). The 18 °C contour lines were created using the Spatial Analyst extension in ArcMap 9.2. Distances (km) were calculated in ArcMap from the middle of each survey site to the nearest point on the 18 °C SST contour line for the week prior to the survey. Distances were averaged across the sites for a survey-specific distance.

Summary statistics were calculated overall and by site. Items making up 1% or more of the debris category total were tabulated. We used ANOVA to test for site differences in total debris, items and pieces; Fisher's Least Significant Difference was used to compare among sites. We used contingency tables to determine whether the items versus pieces distribution varied among sites. We fit linear and polynomial models to determine whether total debris, items, and pieces (summed across sites), and distance to the 18 °C SST isotherm varied by month. We used the square-root transformation for the counts and the log transformation for the distance to stabilize model variances. We used Spearman's rho to assess a relationship between distance to the 18 °C SST isotherm and total debris, items, and pieces. Significance was assessed at alpha = 0.05 and trends were assessed at alpha = 0.10 for all tests. Analyses were done using the statistical package R version 2.7.0 (R Development Core Team, 2009).

The 23 surveys resulted in collection of 32,696 debris elements (identifiable items and pieces) with a total weight of 740.4 kg. Pieces composed 72.2% of the total and had a weight of 109.8 kg; 91.0% of the pieces were made of plastic materials, 7.2% were foamed plastic, and 1.6% were rubber fragments from sandals. Chemical analysis of the 71 sampled pieces indicated that 56% were polyethylene, 30% were polypropylene, 7% were ethylene vinyl acetate, and 7% were miscellaneous [e.g., polymers not of interest such as polybutadiene (i.e., synthetic rubber) or inorganic material such as calcium carbonate]. The single piece made of calcium carbonate appeared to be a degraded fishing float (smooth cylindrical shape with a hole through the middle).

For the identifiable items (9084 items, 27.8% of total), 88.4% of the items were in the fishing/aquaculture/shipping-related and beverage/household products-related debris categories (Table 1). The next most common category was medical/health/personal items at 4.9% of items (Table 1). In the fishing/aquaculture/shipping-related category, 83.4% of the items were oyster spacer tubes, rope, and buoys/floats (Table 1). In the beverage/household products-related category, 82.9% of the items were bottle caps, caps/lids, and plastic beverage bottles (Table 1). In the medical/health/personal items category, 81.7% of the items were toothbrushes, shoes/shoe soles, and hair brushes/combs (Table 1). In the smoking-related category, 100% of the items were cigarette lighters.

Spatial variation was found on Sand Island with total debris load varying by site (all tests, $P < 0.001$). Specifically, the sites that faced or were oblique to the North Pacific Gyre had the most debris, both identifiable items and pieces (Table 2). In terms of composition, sites facing or oblique to the Gyre received a significantly higher proportion of pieces (>70% pieces, all 3 sites) and lower proportion of identifiable items (<30%, all sites) compared to the site facing away from the Gyre (53% pieces and 47% identifiable items; $P < 0.0001$).

Debris loads varied significantly across months for total debris loads (quadratic model, $P < 0.001$), items (quadratic model, $P < 0.001$), and pieces (quadratic model, $P = 0.01$). Identifiable items were lowest during April–August, with loads being about a fifth of what was found during December–January (Table 3). Pieces were lowest during June–August with loads being about an eighth of what was found during December and January (Table 3). The distance of the 18 °C SST isotherm to the Atoll also varied by month (quadratic model, $P < 0.001$). The 18 °C SST isotherm was closest to the Atoll January–April (Table 3). There was a tendency for total debris to be higher when the isotherm was closer to the Atoll (rho = −0.41, $P = 0.054$); this was true for items (rho = −0.37, $P = 0.083$) and pieces (rho = −0.036, $P = 0.087$).

There is now a baseline of information on beached marine debris for Midway Atoll. Large amounts of debris were found on the beaches of Midway Atoll; net pieces were also found though the largest nets are reported to be caught on the fringing reefs (Donohue, 2003). The chemical analysis of the pieces indicates that the majority of pieces likely came from items related to food

Table 1
Percentages of debris items by category found on 23 surveys carried out on four 150 m sites on Sand Island, Midway Atoll, June 2008–July 2010. Category percentages are calculated in relation to total identifiable items collected; within-category percentages are calculated in relation to the category total.

Category	Item	Category percentage	Item percentage
Fishing/aquaculture/shipping-related debris		46.2	
	Oyster spacer tubes		34.5
	Rope		30.4
	Buoys/floats		18.5
	Eel trap cones		3.9
	Crates		2.5
	Fish/laundry baskets		1.5
	Nets		1.5
	Fishing lightsticks		1.3
	Strapping bands		1.3
	Light bulbs/tubes		1.0
	Black plastic ties (Aquaculture)		1.0
	Items < 1% of category		2.6
Beverage/household products-related debris		42.2	
	Caps/lids (other)		34.9
	Bottle caps		37.4
	Beverage bottles (plastic)		10.6
	Misc. plastic bottles		7.0
	Beverage bottles (glass)		6.6
	Misc. glass bottles		3.0
	Items < 1% of category		0.5
Medical/health/personal items		4.9	
	Toothbrushes		42.5
	Shoes/shoe soles		23.5
	Hair brushes/combs		15.7
	Office supplies		13.2
	Other medical/ health and beauty aids		3.1
	Clothes hangers		2.0
Smoking-related debris		2.1	
	Disposable cigarette lighters		100
Toys/sport equipment		1.9	
Appliances/equipment		0.9	
Construction material		0.8	
Food containers		0.7	
Plastic bags		0.2	
Automotive parts		0.1	

Table 2
Average amount per 150 m (standard error) of beached debris by site based on 23 surveys carried out on Sand Island, Midway Atoll, June 2008–July 2010. Within a column, values with the same superscript are not significantly different from each other at $\alpha = 0.05$.

Site	Side of Island	Orientation to North Pacific Gyre	Total debris	Identifiable items	Pieces
1	North	Facing	528.0^a (89.2)	144.7^a (20.2)	383.3^a (78.2)
2	North	Facing	477.6^a (97.1)	132.1^a (24.2)	345.5^a (24.2)
3	West	Oblique	324.7^a (65.2)	75.2^b (15.2)	249.5^a (53.5)
4	South	Facing away	91.3^b (12.1)	43.0^b (5.6)	48.3^b (7.2)

Table 3
Average amount per 150 m (standard error) of beached debris by month from surveys carried out on four sites on Sand Island, Midway Atoll, June 2008–July 2010. N = number of surveys per month. Within a column, values with the same superscript are significantly lower from the other values at $\alpha = 0.05$. The 18 °C SST isotherm is a proxy for the Subtropical Convergence Zone.

Month	N	Total debris	Identifiable items	Pieces	18 °C SST isotherm distance (km)
January	2	2476.5 (619.5)	770.5 (21.5)	1706.0 (641.0)	338.3^a (11.8)
February	2	2131.5 (882.5)	545.0 (15.0)	1586.5 (867.5)	268.2^a (30.8)
March	2	1243.0 (206.0)	402.0 (31.0)	841.0 (237.0)	301.3^a (72.4)
April	2	1059.5 (158.5)	267.0^a (42.0)	792.5 (116.5)	429.5^a (97.4)
May	2	1302.0 (188.0)	303.5^a (42.5)	998.5 (145.5)	470.2 (14.4)
June	3	304.7^a (24.1)	128.7^a (23.3)	176.0^a (22.6)	661.7 (16.6)
July	3	463.30^a (193.5)	164.7^a (71.3)	298.7^a (122.2)	1099.8 (38.2)
August	2	407.0^a (195.0)	171.5^a (110.5)	235.5^a (84.5)	1464.1 (241.8)
September	1	2505	604	1901	1311.1
October	1	2422	525	1897	1173.2
November	1	2767	388	2379	849.0
December	2	2729.5 (1745.5)	884.0 (54.0)	1845.5 (1691.5)	608.8 (39.0)

packaging and cutlery, bottles, ropes, pipes/tubing, cans/buckets, and bags; these items can come from ships but beach surveys also point to land-based sources for these items (Ribic et al., in press). Debris generated from ocean-based activities that occur in near-shore environments of Pacific Rim countries are being transported to Midway, as evidenced by the aquaculture items found on the surveys. Crab traps and floats from the state of Oregon, US, were recently found in the Monument (Ebbesmeyer et al., 2012), documenting the connection of the Monument to activities of Pacific Rim countries.

The debris loads on Sand Island are higher than the maximum loads found on French Frigate Shoals, located south of Midway Atoll in the same Northern Hawaiian Islands archipelago (Morishige et al., 2007) (Fig. 1). The debris on Sand Island also exhibited a seasonal pattern, not seen on French Frigate Shoals (Morishige et al., 2007). Some of the seasonal variability on Midway Atoll is likely due to the geographical location of the Atoll with respect to the Subtropical Convergence Zone (STCZ). Midway Atoll is closer to the STCZ, with its concentration of marine debris (Pichel et al., 2007), than is French Frigate Shoals (Fig. 1), so the effects of the seasonal movement of the STCZ (Bograd et al., 2004) are more likely to be found on Midway Atoll. Ribic et al. (in press) found no effect of the STCZ on beach debris deposition patterns on O'ahu, Hawai'i, which is even further from the STCZ than French Frigate Shoals (Fig. 1).

Some of the identifiable items, as well as debris pieces, we found on the beaches of Sand Island have also been found in Laysan Albatross (*Phoebastria immutabilis*) chicks (Auman et al., 1997; Petit et al., 1981); these items and pieces are fed to chicks by the adults which feed in the North Pacific Gyre (Young et al., 2009). The large amount of plastic pieces on Sand Island, including pieces smaller than those collected in our study (McDermid and McMullen, 2004), is indicative of the larger issue of plastic degradation on beaches (Corcoran et al., 2009). This baseline information gives the managers at Midway Atoll information to plan mitigation strategies, a way to measure success, and a benchmark against which to determine changes due to large-scale events such as the 2011 Japanese tsunami.

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