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Baseline

Nearshore sea surface macro marine debris in Maui County, Hawaii: Distribution, drivers, and polymer composition

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ABSTRACT

Located within the subtropical convergence zone, the Hawaiian archipelago is subject to high debris loads. This paper represents the first study to determine the spatial and temporal trends of floating macro debris quantities and polymer composition within Maui County waters. Ocean surveys were conducted from 2013 to 2017 and collected 2095 debris items of which 90% were plastic. Attempts to categorize items by source resulted in only 6% likely from land, 12% from ocean-based sources, 50% from either land or ocean, and 32% from unknown sources. Results found a multi-step process for debris accumulation, with temporal trends linked to survey day and year and spatial trends linked to ocean processes. High- and low-density polyethylene and polypropylene accounted for the majority of polymer types. The results of this study demonstrate minimal debris in Maui originates from land/local sources, and the importance of baseline data to guide further research and mitigation measures.

Marine debris poses a considerable threat to marine life, biodiversity, and ecosystems (Sheavly and Register, 2007; Galloway et al., 2017) and has been identified as a stressor for a variety of marine life (Moore, 2008; Currie et al., 2017). Marine debris can be classified into three categories describing its likely source: land, ocean, and "general", which encompasses both or either land and ocean, as described by Ribic et al. (2012). Previous research has identified ocean-based debris as the primary source of Hawaiian marine debris (Donohue et al., 2001), with proportionately higher ocean-based debris when compared to other regions in the Pacific (Ribic et al., 2012). Once reliable data on where marine debris originates and how it is introduced into the marine environment is available, targeted efforts to stop this problem at the source can be implemented.

Current knowledge of ocean currents in the North Pacific suggests three high-density areas of debris accumulation based on convergence zones (Wakata and Sugimori, 1990; Kubota, 1994; Van Sebille, 2015). One such zone is located just north of the Hawaiian Islands, and has been found to accumulate debris (Donohue et al., 2001; Pichel et al., 2007; Goldstein et al., 2013) (Appendix Fig. 1). The origins of debris north of Hawaii varies greatly, and the resulting accumulation is the result of multi-step processes starting with the Ekman convergence zone, transport via the geostrophic currents, and finally Ekman drift (Kubota, 1994). Marine debris accumulating north of the Hawaiian archipelago can travel through various marine ecosystems including coastlines, remote islands, the open ocean, and subtropical gyres (Derraik, 2002; Barnes et al., 2009). Some work has been conducted to document the rates and process of marine debris accumulation in the Northwestern Hawaiian Islands (Kubota, 1994; Donohue et al., 2001; Dameron et al., 2007; Pichel et al., 2007), but these efforts have been minimal and rates are likely out of date. Further, this work does not include the coastal waters of the Main Hawaiian Islands.

Currie et al. (2017) presented the first study quantifying the amount and type of marine debris in the nearshore waters of Maui county and related this to cetacean distribution to identify areas where marine debris ingestion or entanglement may present a high risk to marine mammals. Ingestion and entanglement of marine debris by biota has been well documented (Kühn et al., 2015), and effects of plastics on marine life are polymer dependent (Rochman et al., 2013). The current study expands the previous study (Currie et al., 2017) by performing polymer identification and statistical models to find local and ocean-wide variables that explain the accumulation of plastic marine debris floating in Maui County's nearshore waters.

Plastic marine debris is comprised of many different polymers that have specific chemical compositions defining their physical and chemical properties, leading to different environmental fate and effects. Polymer composition of marine debris items will affect vertical

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stratification in the water column and influence interactions with marine organisms (Jung et al., 2018). Debris collected from the surface is expected to consist of floating low-density polymers such as polyethylene (PE) and polypropylene (PP) as opposed to sinking high-density polymers such as polyethylene terephthalate (PET) (Jung et al., 2018). As plastic marine debris is a growing problem in Maui County, a need for identifying polymer type is crucial for understanding the behavior of debris in the ocean environment and to know which polymers whales, dolphins, and other marine life will be exposed to in order to reduce their impact.

Blickley et al. (2016) monitored shoreline debris in Maui and found debris loads were linked to ocean based processes such as winds and currents as well as beach exposure and location. At a single site shoreline debris accumulation rates were as high as 1460 items per day within a 100 meter section, which was largely attributed to ocean based sources (Blickley et al., 2016). A clearer understanding of nearshore debris loads within the waters surrounding the Main Hawaiian Islands should be determine to supplement Blickley et al. (2016) and allow for a better understanding of which mitigation measures would be most effective for Hawaii. This study quantified macro (> 1 cm diameter) marine debris floating in the nearshore waters of Maui County as a complement to existing shoreline surveys. The objectives of this study were to: (1) identify factors influencing marine debris accumulation; and (2) characterize debris type including polymer composition, source (ocean, land, or general), and amount of marine debris within the study area.

The nearshore waters of Maui county that made up the study area (center: 20.73623°N, 156.69085°W) are semi-enclosed by the islands of Maui, Molokai, Lanai, and Kahoolawe and located within the Hawaiian Islands Humpback Whale National Marine Sanctuary. The channels between the islands are akin to drowned land bridges that once connected the surrounding islands. The study area consists predominantly of nearshore habitats with gently sloping shoreline gradients that extend to more complex bathymetry of seamounts and ridgelines (Grigg et al., 2002). The majority of the study area consists of drowned reef features and sandy basins with a depth of < 200 m; however, some areas south of Lana'i reach depths up to ≈600 m.

The detailed methods of data collection for this study are previously described in Currie et al. (2017), with a brief synopsis provided here. Line transects, separated by one nautical mile (1.85 km), were conducted within the leeward waters, up to 18 km from the coasts, of the four islands (Maui, Molokai, Lanai, and Kahoolawe) that comprise Maui County, Hawaii and covered 1004 km^2. Line transects were followed using the research vessel's onboard GPS. The starting point of each survey was chosen randomly at the beginning of each survey day. The transect lines, as followed using the onboard GPS, are presented in Fig. 1, with survey effort shown in Fig. 2. If debris was sighted during a transect, the transect was paused while the vessel changed course to pick up the debris. Once the debris was removed and documented, the vessel navigated back to the transect line and effort was resumed from the pause position. To ensure there were no missed occurrences of debris, all sightings of marine debris, regardless if on transect or travelling between transects, were recorded and used in subsequent analysis.

A minimum of one survey day/week was attempted and planned for the day with the best weather forecast, to allow observers the best conditions for visibility. If no suitable weather days (Beaufort and Douglas Sea States were > 3) were available, multiple surveys were conducted during the next suitable weather window. From April 6, 2013 to October 12, 2017, 767 line transect surveys for macro (> 1 cm diameter) floating debris were completed over 260 days from an 8 m engine-powered research vessel. The collection of debris for this project was done in conjunction with a systematic line transect study for odonotocetes, and it is important to note that despite conducting line transect surveys, distance sampling procedures were not followed for the debris items collected. Therefore, no effective transect width could be calculated and the survey width was limited to the sighting distance of the observer. As such, the results presented here represent presence-only sightings, which have not been corrected for detectability. The transect surveys ensured sufficient coverage of the survey area, but not adhering to systematic survey methods allowed for the highest number of debris items to be collected and was deemed most appropriate for this study.

All marine debris location data were imported into ArcGIS 10.6 (Environmental Systems Research Institute, 2012) and mapped with the World Mercator projection, using the WGS 1984 datum. To determine spatial trends in debris quantities over the entire duration of the study period, the study area was divided into 1004 grid cells each with an area of 1 km^2 (1 km × 1 km). Each grid cell was classified by the count of debris items occurring in that cell and the total survey distance (km) travelled within the boundaries of that cell from April 6, 2013 to October 12, 2017. Quantities of marine debris were summarized per grid cell by dividing the sum of debris counts by the sum of survey effort (km) within each grid cell, resulting in final units of number of debris items/km/grid cell, which henceforth will be referred to as spatial quantities. Grid cells with no survey effort were dropped and not displayed in the final spatial trend map.

All floating macro debris (> 1 cm diameter) items within sighting distance were recorded during the survey period. As such, results presented here likely represent an underestimation of all debris items because smaller items, particularly micro and nano debris items, were not sampled. Observations were undertaken by two experienced observers stationed on the port and starboard sides of the vessel, as well as the boat operator who was stationed at the helm using a continuous scanning methodology (Mann, 1999) by naked-eye or reticle binoculars (Bushnell 7 × 50), while a fourth person acted as a data recorder. No elevated observation platform was used and, as such, each observer's feet were standing ≈28 cm above the waterline. To ensure minimal influence of weather on detectability of debris, surveys were only conducted in the absence of rain and when Beaufort and Douglas Sea States were ≤3. However, there is likely some un-corrected influence of weather on the detectability of debris that should be acknowledged, and the debris counts recorded for this study may represent an underestimate of the true count. When a piece of debris was sighted, the item was collected (if size and conditions allowed) and latitude, longitude, type of material, and percent of organism coverage (biofouling) on the debris item were recorded. Percent organism coverage was determined by visual inspection of the debris item and estimating the proportion of biofouling with respect to total surface area (See Appendix Fig. 2). If the item could not be collected given the feasibility of removing it from the water, it was photographed and recorded but left in the ocean.

To be consistent with the national debris monitoring program, all debris classification was based on standardized source categories established by the United States Environmental Protection Agency (Escardó-Boomsma et al., 1995) and detailed in Ribic et al. (2012). Debris was divided based on the type of debris: plastic, metal, glass, rubber, clothing/fabric, processed lumber; and probable source category: ocean, land, general, or unknown. Ocean-based debris related to ocean recreation and commercial fishing; land-based debris related to land-based recreation and activities; general-sourced debris related to items that could originate from either ocean- or land-based sources (Ribic et al., 2012); and unknown-sourced debris consisted of debris fragments that could not be identified and therefore could not be reliably placed in a source category. The probable source categories (ocean, land, and general) were adapted from Ribic et al. (2012) and the debris item division used in this paper is presented in Appendix Table 1. It should be noted that debris was classified as best as possible in the most likely source category, but the potential for overlap between categories may exist and should be considered when interpreting results.

To gain a better understanding of the type of plastic debris that was collected throughout the survey period, all plastic debris items were

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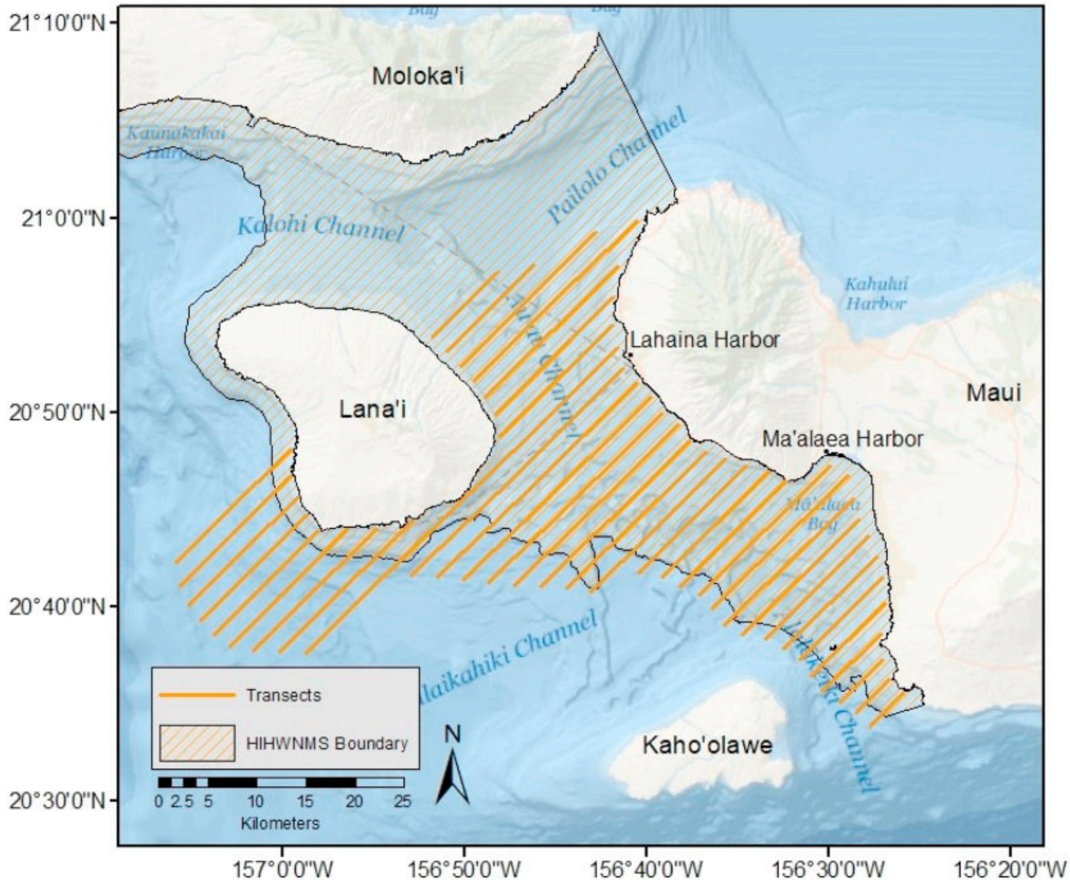

Fig. 1. Map depicting study area and line transects surveyed within Maui County, Hawaii from April 6, 2013 to October 12, 2017 and overlaid with the Hawaii Humpback Whale National Marine Sanctuary (HIHWNMS).
Note: The study area covers approximately ~20% of the HIHWNMS.

subclassified into nine main categories: foam fragments, food packaging fragment, net/rope fragments, plastic fragments, plastic bottles, plastic bags, buoys, jugs and other. Proportions of debris within these nine categories were summarized and presented in the results.

To help identify what items were commonly found throughout the survey period, all intact items that were recorded a minimum of 15 times were further subclassified into 14 categories regardless of debris type: aluminum cans, balloons, beach toys, bottle caps, buckets, buoys, cups, fishing gear, food containers, food wrappers, jugs, nets/ropes, plastic bags, and plastic bottles. Proportions of debris within these 14 categories were summarized and presented in the results.

Photos of debris items were visually inspected for writing or characters that may indicate country of origin (See examples in Appendix Fig. 3). If non-English writing was present, country of origin was

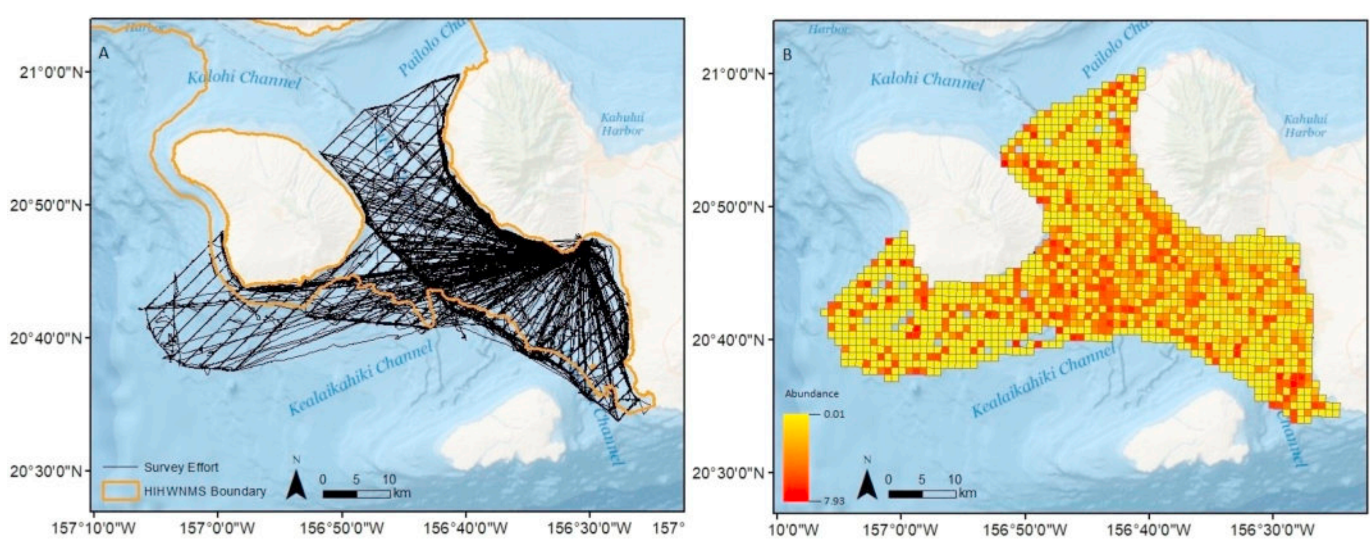

Fig. 2. Map showing (A) survey effort, and (B) marine debris spatial quantities (items/km of survey effort/grid cell) between April 6, 2013 and October 12, 2017 within Maui County, Hawaii.

assumed based upon the language displayed on the debris item.

To assess sources and composition, results were summarized for each survey year by dividing yearly sum of debris counts within each of the four debris source categories (ocean, land, general, unknown) by the sum of the yearly survey effort (km). This resulted in final units of debris count/km/year. A two way ANOVA was used to test for differences in yearly quantities across the source categories and year. To account for unequal sample sizes within the independent variables, a Type III sums of squares was employed in our ANOVA using the Anova () and aov() functions in R (R Core Team, 2017; Fox and Weisberg, 2011). Before conducting the statistical analyses, the lack of normality was addressed by log transforming the data prior to analyses (Zar, 1984).

Debris located within 50 m of each other were classified as a cluster of debris and considered an indicator of localized high accumulation. The mean number of debris items per cluster was calculated for each year to determine if cluster concentration varied with time.

All hard plastics collected from April 19, 2017 to July 11, 2017 were analyzed with a PerkinElmer attenuated total reflectance Fourier transform infrared spectrometer Spectrum Two (Waltham, MA) (ATR FT-IR) for polymer identification using the method described in Jung et al. (2018). Air-dried pieces were weighed to ± 1 g or for smaller pieces to ± 0.00001 g. Pieces were not cleaned prior to analysis, but were cut with a razor blade when needed to expose a clean, smooth, and uncontaminated inner surface. Items that contained more than one part (e.g., a bottle and a cap) were separated into multiple pieces for analysis. All samples were assigned a color, opacity, and weathering code. Weathering codes were assigned visually as 1 = mild, 2 = moderate, and 3 = severe based on the intensity of square fracturing on the surface of the sample with 1's having the least and 3's having the most (Appendix Fig. 4). Polymers were identified from spectra using absorption bands, criteria, and the decision tree described in Jung et al. (2018). A float test in ethanol and deionized water solutions with densities of 0.931 and 0.941 g/mL was performed as outlined in Jung et al. (2018) on 21 unknown PE samples to differentiate between low- and high-density polyethylene (LDPE, HDPE).

Daily debris counts (items/day) were analyzed separately for land-based, ocean-based, general-source, and unknown-source as processes leading to changes in accumulation are likely to be different for each category. However, there is value in understanding if all debris collected, regardless of source, is influenced more by land or ocean drivers. To determine this, two models of daily debris counts (items/day) were tested, one model using only land-based variables/processes and a second model using only ocean based variables/processes, as described below. The set of drivers (land or ocean) resulting in the lowest Akaike's Information Criterion (AIC) model was then considered to be the most influential set of variables for describing overall debris trends within the study and presented in the results.

To account for potential nonlinear relationships between debris counts and explanatory variables (Ribic et al., 2012), Generalized Additive Models (GAM) were constructed using the 'mgcv' package in R (Wood, 2017), using a gamma of 1.4 to avoid overfitting (Ribic et al., 2012; Wood, 2006). Daily debris counts (items/day) were modelled for each source category and log-transformed for normality as a function of survey variables, environmental variables, and process-based variables (partially adapted from Ribic et al., 2012 and explained below), with an offset term for daily survey effort (km/day). Explanatory variables were tested for pairwise correlations using the stats package in R (R Core Team, 2017). To account for non-normality in variables, the Spearman correlation coefficient (*rs*) was used to assess correlations. If variables were highly correlated ($rs \geq 0.7$) (Gonzalez-Suarez et al., 2013) only the variable that provided the lowest AIC value was retained.

To model temporal trends, a coded survey day (Ribic et al., 2012) was used, where 1 represented the first survey day (April 6, 2013) and 1634 represented the last survey day (October 12, 2017). Variations in within-year deposition may be the result of human activity and/or extreme weather events, which as described in Ribic et al. (2012), can consistently be captured with month. Therefore, within-year trends were modelled using month and between year variations using year as an explanatory variable.

The following variables were associated with each survey date using historical National Data Buoy Center (NDBC) data (www.ndbc.noaa.gov): wind speed (km/h) and direction (degrees), peak gusts (m/s), wave height (m), dominant and average wave period (s), dominant wave direction (direction), sea level pressure (hPa), air temperature (Celsius), and sea surface temperature (Celsius). A total of 24 active buoys are deployed within 500 km of the Hawaii islands chain, with the majority concentrated around the island of Oahu (National Climatic Data Center's (https://www.ncdc.noaa.gov), 2018). Two of these active buoys were selected based on their proximity and location relative to the study area and the metrics they recorded. The two data sources were evaluated independently for analysis of ocean-based debris, as variables differed between the two sources. Only the source data set providing the lower AIC model was presented in the final results. Data were compiled from April 2013 to October 2017 from the following two data buoys: Station 51,205 (NDMC, 2018a) located 41 km NW of center of the study region (center: 20.73623°N, 156.69085°W), and Station 51,003 (NDBC, 2018b) located 436 km WSW of the center of the study region. Final selection of stations 51,205 and 51,003 for analysis was based on the availability of continuous data for the entire duration of the study period as well as physical location. Before analysis was conducted, data were quality controlled by removing missing data, denoted with variable number of 9's. To assess the impacts of these variables on daily debris count, weather variables were modelled at the time of survey and the day prior.

Debris retention and accumulation on beaches in Maui is known to be impacted by ocean factors such as wave and tide height (Blickley et al., 2016). As such, both land and ocean variables were considered when evaluating potential drivers of land-based debris. For land based variables, each survey date was associated with the following data taken from station KLIH1 – 1615680 (National Climatic Data Center's (https://www.ncdc.noaa.gov), 2018) located 26 km NE of the center of the study region (center: 20.73623°N, 156.69085°W): average daily wind speed (km/h) and direction (degrees), fastest wind speed (km/h) and direction (deg), and precipitation (Y/N). Ocean-based variables were taken from Station 51,205 (NDMC, 2018a).

Each month of the survey period was classified by the presence of the following: (1) El Nino-Southern Oscillations (ENSO) event, (2) La Nina-Southern Oscillations (LNSO) event, or (3) no event. Data used in analysis were taken from the NOAA Climate Prediction Center (2018) ENSO monthly categorization table.

Monthly sea surface temperatures from April 2013 to October 2017 were downloaded from NOAA Earth System Research Laboratory Physical Sciences Division (2018). The 1.0° latitude by 1.0° longitude global grid was loaded into ArcMap (Environmental Systems Resource Institute, 2018) and the contour tool in the spatial analyst extension was used to create an 18 °C isotherm. The proximity (distance in km) of this isotherm to the center of the study region (center: 20.73623°N, 156.69085°W) was then calculated in ArcMap. Each month of the survey period was then classified by the distance to the 18 °C isotherms. The 18 °C isotherm can be used as an index for the proximity of the Subtropical Convergence Zone (STCZ) (Pichel et al., 2007), with the expectation that debris loads are higher when STCZ is closer to Hawaii (Ribic et al., 2012).

To determine if tourism influenced land-source debris items, the total monthly visitor days from 2013 to 2017 were obtained from the Hawaii Tourism Authority (HTA, 2018). Monthly visitor days, calculated by multiplying total monthly visitor count (tourists/month) by the average monthly visitor duration (days), ranged from 1.30 million to 2.10 million. To facilitate analysis, monthly visitor days were classified into four categories ranging from 1 (lowest number of visitor days) to 4 (highest number of visitor days) as follows: 1 (1.30–1.49 million); 2

(1.50–1.69 million); 3 (1.70–1.89 million); 4 (1.90–2.10 million). All 54 months of the survey period were assigned a value of 1 to 4, corresponding to the appropriate ranges as determined from HTA data set. To facilitate interpretation of results, the average monthly visitor days and air temperatures (°C) from January 2013 to December 2017 for Maui were summarized and are presented in Appendix Fig. 5.

Given the potential variability in general- and unknown-source debris, a combination of ocean and land-based variables described in previous sections were used in selecting the best general- and unknown-source models, similar to that of Ribic et al. (2012).

Analysis began with testing of a full candidate model, including all possible explanatory variables and using AIC to rank the models (Burnham and Anderson, 2002) and determine which variables were candidates for removal from the model. Variables were then removed in a stepwise manner until a minimum AIC value was reached. Significance was assessed at $\alpha = 0.05$ and the minimum AIC models were presented in the results.

From April 6, 2013 to October 12, 2017, 38,270 km was surveyed (Fig. 2A), and 2095 pieces of marine debris were documented. Marine debris was observed in all parts of the survey area (Fig. 2B). Debris spatial quantities (total debris items/km of survey effort/grid cell) over the total survey period showed a trend of higher accumulation between the islands of Maui, Lanai, and Kahoolawe in the area where the Auau, Kealaikahiki, and Lalakeiki channels meet (Fig. 2B).

Of the 2095 debris items documented, the majority of the debris was classified as general-sourced debris (Fig. 3A). Plastics were the predominant type of debris recorded within the study area, accounting for 90% of total debris (Fig. 3B).

Quantities of land, ocean, general-source, and unknown-source debris varied between years, with 2017 having the highest quantity of debris observed over the five year study period (Table 1). Quantities were found to vary between year (Sum Sq: 0.73, F-value: 33.40, p-value: < 0.001) and source category (Sum Sq: 1.58, F-value: 34.42, p-value: < 0.001). Of the debris that could be identified as land or ocean based, the majority was ocean based; which in some years was four times the concentration of land based debris (Table 1).

The proportion of ocean-based debris was highest in 2013. There was a general decreasing trend in general-source debris and a general increasing trend of unknown-source debris throughout the survey period. Land-based debris increased with time having highest proportion in 2016 and 2017 (Table 1).

An overall increase in weekly debris counts (items/week) was observed throughout the study period, with a steep increase from March–May in 2017 (Fig. 4). A 354.5% increase in all debris quantities (items/km effort) was observed in 2017 when compared to average of the previous four years, the majority of which was attributed to general- and unknown-source debris (Table 1). With the exception of 2015, the maximum yearly cluster concentration (number of debris items accumulated within 50 m of each other) increased with year (Table 1). The mean cluster size was highest during 2016 and 2017, with maximum debris cluster in 2017 nearly double the average of the previous four years (Table 1).

The majority of plastic debris items consisted of plastic (36%) and foam (14%) fragments (Fig. 5A). For items that were found whole, plastic bottles (16%) and buoys (14%) accounted for nearly one-third of these collected (Fig. 5B).

Of the debris documented, 73.3% (n = 1536) exhibited some form of biofouling, with plastics comprising the largest proportion (n = 1425, 92.7%) of biofouled items. The amount of biofouling varied by item, but was highest for buckets (avg = 55.8%) and lowest for balloons (avg = 1.4%) (Fig. 6). Eight items contained biofouling not native to Hawaiian waters, including blue mussels (*Mytilus edulis*), chitons (*Mopalia*), and/or limpets (*Lottia*), which were initially identified in the field before being photographed and sent to the Department of Aquatic Resources for confirmation when possible. Foreign writing allowed for assessment of probable country of origin for 23 items. Of these items, 10 items displayed Japanese characters, 7 displayed Chinese characters, and 4 displayed Korean characters. Two items displayed characters which could have belonged to either the Japanese or Chinese languages, and therefore could not be identified to a country. The majority of these items (13 items, 56.5%) were identified as coming from ocean sources, while the remaining 10 items could have originated from either land- or ocean-based sources.

The subset of 252 hard plastic debris items collected from April 14 to July 11, 2017 was analyzed to determine polymer composition. The majority (52.5%) of debris items analyzed was classified as severely weathered, with the remaining items being mildly (27%) and moderately (25.5%) weathered. Weathering code did not impact polymer composition, because pieces were cut to reveal an inner surface for ATR FT-IR measurements. All pieces consisted of polymers that would float in seawater, based on the polymer density, except for one PET bottle. HDPE, LDPE, and polypropylene (PP) accounted for the largest proportion of debris sampled (Fig. 4a & b). PP makes up the greatest proportion of sampled debris by mass, while HDPE and LDPE make up the greatest proportion by count (Fig. 7A & B).

The lowest AIC model for the entire dataset, regardless of debris source category, included ocean-based sets of variables/processes. Data from Buoy 51,003 with a one day offset resulted in the best fit model for this dataset. The most significant driver of debris counts (items/day) was coded survey day (Table 2; Fig. 8B). Additional factors, in decreasing order of significance included: the interaction between wave height (m) and dominant direction (degrees) (Table 2; Fig. 9), non-

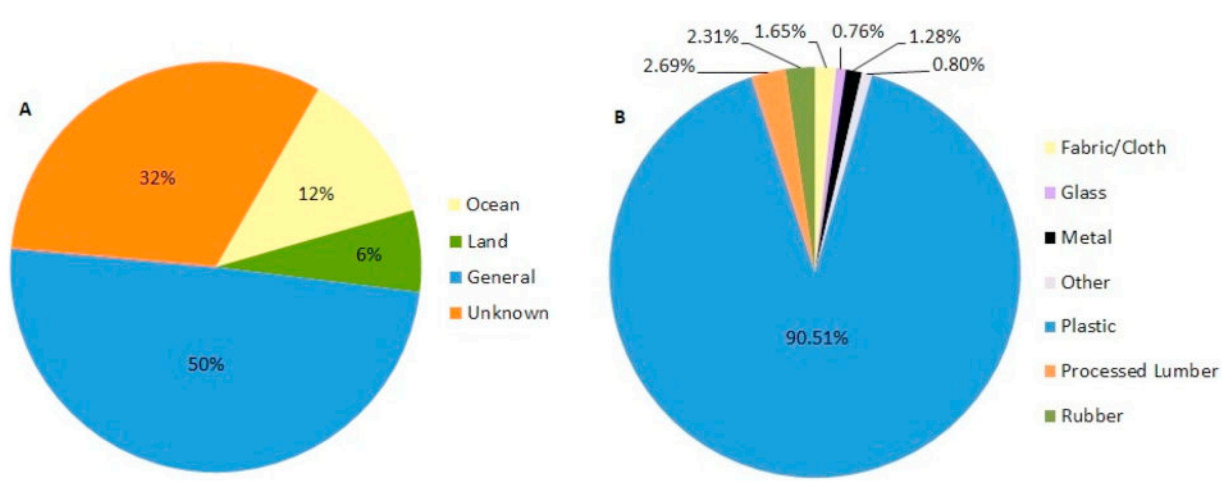

Fig. 3. Proportions of debris (A) origin and (B) material collected between April 6, 2013 and October 12, 2017 within the coastal waters of Maui County, Hawaii.

Table 1
Yearly quantities, proportions, and cluster sizes of marine debris items summarized by total and source categories documented between April 6, 2013 and October 12, 2017 within the coastal waters of Maui County, Hawaii.

Year	2013	2014	2015	2016	2017
Debris summary					
Total debris count	402	276	236	328	853
Total survey effort (km)	5985	7963	5067	4218	4248
Total survey days	47	62	43	36	31
Quantities of debris					
Quantities of all debris (items/km effort)	0.067	0.036	0.048	0.080	0.201
Quantities of ocean-based debris (items/km effort)	0.013	0.006	0.008	0.011	0.009
Quantities of land-based debris (items/km effort)	0.003	0.003	0.004	0.009	0.009
Quantities of general-source debris (items/km effort)	0.036	0.018	0.027	0.033	0.097
Quantities of unknown debris (items/km effort)	0.015	0.008	0.008	0.027	0.085
Proportions of debris					
Proportion of ocean-based debris	19.40	17.54	17.43	14.29	4.69
Proportion of land-based debris	4.44	8.07	9.13	10.71	4.34
Proportion of general-source debris	53.73	50.88	56.02	41.37	48.53
Proportion of unknown debris	22.39	23.51	17.43	33.63	42.44
Debris clusters					
Mean items/cluster[a] (standard deviation)	1.52 (1.49)	1.43 (1.49)	1.20 (0.88)	1.80 (2.10)	2.21 (3.06)
Maximum items/cluster[a]	10	13	8	14	21

[a] Debris items located within 50 m of each other were considered part of the same cluster.

ENSO/LNSO months (Table 2), and distance to the 18 °C isotherm (Table 2; Fig. 8A). The combination of low wave height (< 1 m) and wind coming from 150° or 350° resulted in high debris counts (Fig. 9). Debris counts fluctuated with distance to the 18 °C isotherm, but there was a general decreasing trend of debris with increasing distance to the 18 °C isotherm (Fig. 8A). Strong temporal trends in debris counts were evident with peaks observed in April 2015 and February 2017, each of which were preceded by dips in debris counts. A significant increase in debris counts was observed during non-ENSO/LNSO months (Table 2).

The lowest AIC model for ocean-based debris was fit using variables from Buoy 51,003, with a 1 day offset. Ocean-based debris counts (items/day) showed significant nonlinear relationships with wind direction, air temperature, and survey date; and significant linear relationships with sea level pressure and wave period (Table 3; Fig. 10). Air temperature could indicate an influence of the STCZ, as temperatures would be coldest in late winter and early spring when the zone is closest to Hawaii. As such, air temperature may represent a lag effect of the STCZ with high accumulation being observed after the zone reaches its closest point to Maui. However, further research is needed to determine the exact lag-time and potential connection between STCZ and air temperature.

Ocean-based debris counts remained fairly constant until June 2016, which saw the sharpest increase in debris until December 2016 followed by the sharpest decrease in debris until October 2017 (Fig. 10B). Peaks in ocean-based debris counts varied based on wind directions, with peaks occurring when wind direction was 0, 75, 125, and 200° (Fig. 10C).

Land-based debris counts showed significant nonlinear relationships with water temperature and average wind speed (Table 4; Fig. 11). Land-based debris counts were highest during low wind speed intervals (6–10 km/h) and high speed intervals (22–24 km/h), with variations from 6 to 12 mph (Fig. 11A). There were minimal changes to land-based

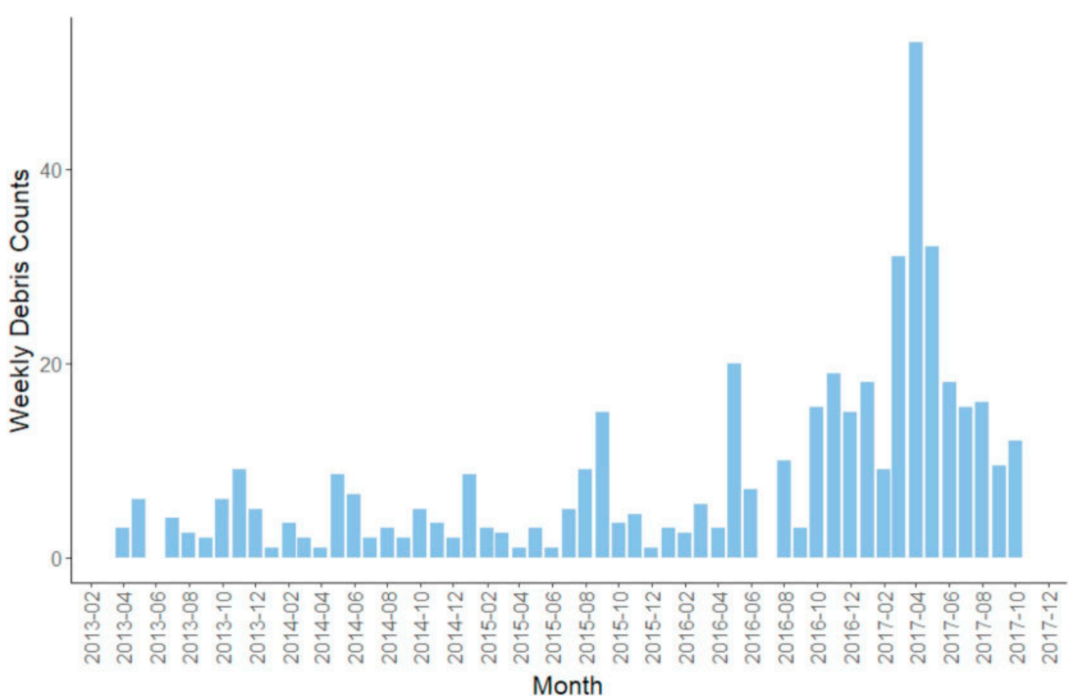

Fig. 4. Weekly counts (items/week) of debris items collected between April 6, 2013 and October 12, 2017 within the coastal waters of Maui County, Hawaii.

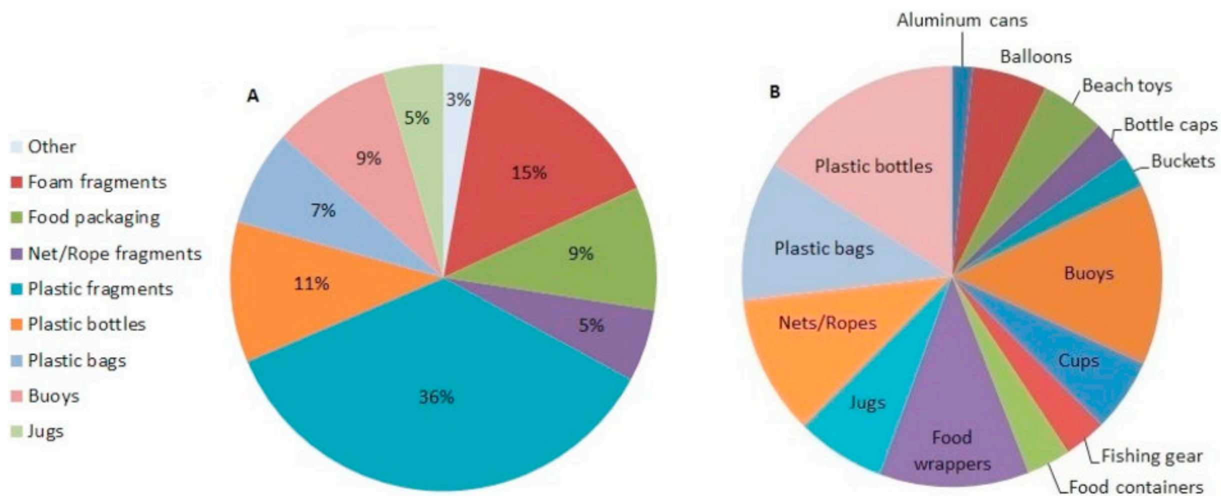

Fig. 5. Proportions of (A) plastic debris items (n = 1986) divided into subcategories and (B) intact debris items (n = 887) divided into commonly sighted subcategories groups collected between April 6, 2013 and October 12, 2017 within the coastal waters of Maui County, Hawaii.
Note: Panels A and B were created separately and the same item may be used in both figures. As such, these figures should be evaluated independently.

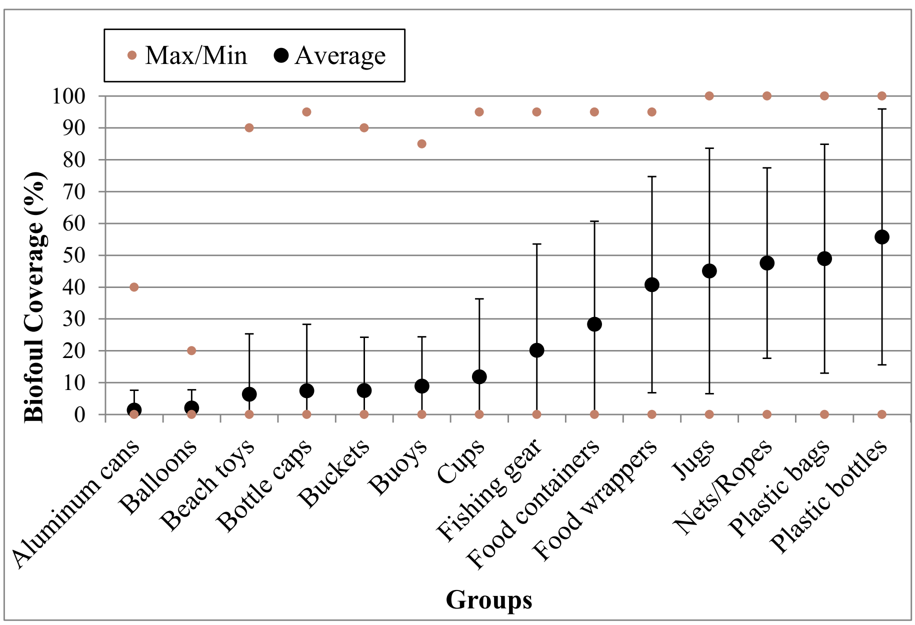

Fig. 6. Average percent biofouling observed on whole debris items divided into identifiable groups collected between April 6, 2013 and October 12, 2017 within the coastal waters of Maui County, Hawaii.
Note: Error bars represent the standard deviations.

debris accumulation on survey days when air temperatures ranged from 24.0 to 25.0 °C, with a gradual reduction in debris seen when temperatures exceeded 25.0 °C (Fig. 11B). The months with the highest temperatures correspond to months with lowest monthly visitor days: August, September, and October (Appendix Table 2).

The lowest AIC model for general-source debris was fit using variables from Buoy 51,003, with a 1 day offset; the same as the ocean-based model. General-source debris counts showed significant non-linear relationships with survey date, and marginally significant linear relationships with year (Table 5; Fig. 12). General-source debris counts gradually declined throughout the survey period (Fig. 12). Although not significant, within year counts showed an increasing positive linear relationship with increasing years (Table 5).

The lowest AIC model for unknown-source debris was fit using variables from Buoy 51,003, with a 1 day offset; the same as the ocean-based and general-source debris models. Unknown-source debris counts showed significant nonlinear relationships with water temperature, and significant linear relationships with survey date, ENSO, wind speed, and peak gusts (Table 6; Fig. 13). Unknown-source debris counts showed a varying trend with temperature (Fig. 13). Significant positive trends of unknown-source debris counts with survey date, southern oscillations, and wind speed were observed, while a negative linear trend was found with increasing peak gusts (Table 6).

The observed variation in significant variables based on marine debris source category aligns with work presented in Ribic et al. (2012). Overall, the difference in the sets of variables included in the lowest AIC model for each source category and for all debris, regardless of source, suggests a wide variety of drivers are likely responsible for the variability in debris quantities observed in the nearshore waters of Maui County. The prevalence of survey date and ocean based variables with a one day offset in four of the five lowest AIC models suggests these processes are linked to temporal and ocean based drivers and are best captured using time and an offshore buoy data set (Buoy 51,003).

As reported in Currie et al. (2017), plastics comprised the majority

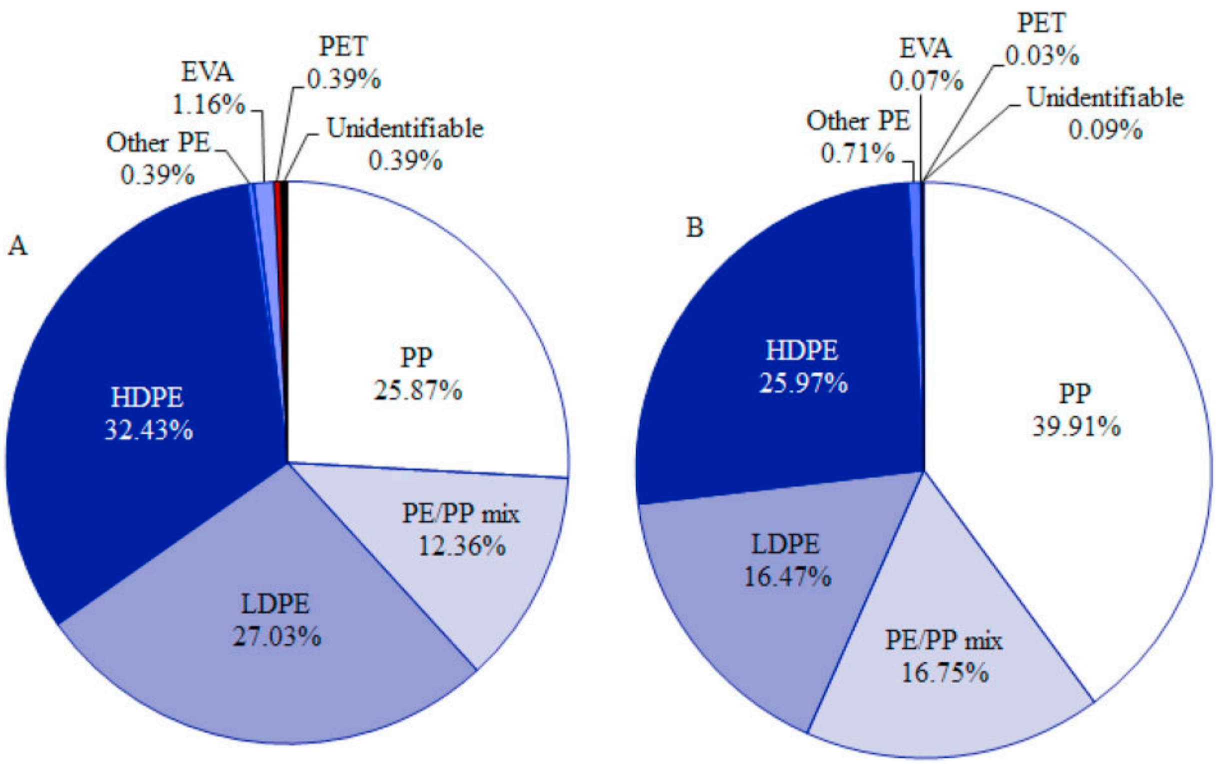

Fig. 7. Percent of polymers identified in debris sub-sample (n = 252) as a function of total (A) count and (B) mass. Low-density polymers expected to float on seawater are shown in white and blues.
Note: Polyethylene terephthalate (PET) (n = 1), high-density polyethylene (HDPE), low-density polyethylene (LDPE), other PE is a piece that had an obvious PE spectrum but with additional non-PE peaks (n = 1), polyethylene and polypropylene mixture (PE/PP mix) as defined in Jung et al. (2018), polypropylene (PP), ethylene vinyl acetate (EVA), and unidentifiable (n = 1) were pieces that produced very noisy spectrum that could not be identified.

of floating macro debris found in this study region; a result that aligns with the known prevalence of floating plastics in the ocean (Coe and Rogers, 1997; Derraik, 2002). The increasing trend in debris quantities throughout the duration of the study aligns with the global trend of increasing debris deposition in our oceans (Eriksen et al., 2014). The large increase in debris quantities observed in 2017 is likely related to the higher number of small scale debris clusters, which were observed more frequently and in larger sizes in 2017. Although observers changed throughout the survey period, the number of observers remained constant. As such, it is unlikely that differences in observers accounted for the substantial increase in debris observed in 2017. Similarly, weather conditions were also kept consistent (BSS and DSS ≤ 3) throughout the study period and weather changes likely do not account for the observed increase.

The predominantly northwest surface currents in leeward areas of Maui County occur, in part, from Ekman transport along with wind-driven eddy effects resulting from the northeast trade winds interacting with the land masses of the islands (Chavanne et al., 2002). These eddies likely result in the convergence pattern of debris seen in the channels that separate the four islands of the region; opposing eddies in the lee of Maui Island may cause areas of lower current velocities, which allows marine debris to accumulate.

Debris from Japan, China, and Korea most likely drifted to the Hawaiian Islands after transport in the Subtropical Gyre and subsequent northwest surface currents toward the leeward waters of Maui (e.g., Chavanne et al., 2002; Howell et al., 2012). Although plausible country of origin was determined via markings on the debris, it is virtually impossible to determine the exact point at which any particular item entered the marine environment. For example, debris with Japanese writing may have entered the ocean in coastal Japan, from an offshore fishing vessel, or from a tourist visiting Hawaii.

The composition of debris presented here supports previous reports that the majority of marine debris in and around the Hawaiian Islands originates from far offshore rather than local land-based sources

Table 2
Results of top generalized additive model used for determining the linear and nonlinear relationships between all debris counts and variables, based on data collected within the coastal waters of Maui County, Hawaii between 2013 and 2017.

Factor		edf[a]	F-value	p-Value	R^2	Dev. expl.
All debris nonlinear	s(18 °C isotherm)	8.22	1.95	0.05	0.45	52.1%
	s(wave height, dominant wave direction)	9.69	2.61	0.003		
	s(survey date)	7.60	7.57	< 0.0001		

Factor		Estimate	t-Value	p-Value	R^2	Dev. expl.
All debris linear	La Nina Oscillation	0.52	0.81	0.42	0.45	52.1%
	No Oscillation	1.35	2.21	0.02		

[a] edf is the estimated degrees of freedom accounting for the smoothing function.

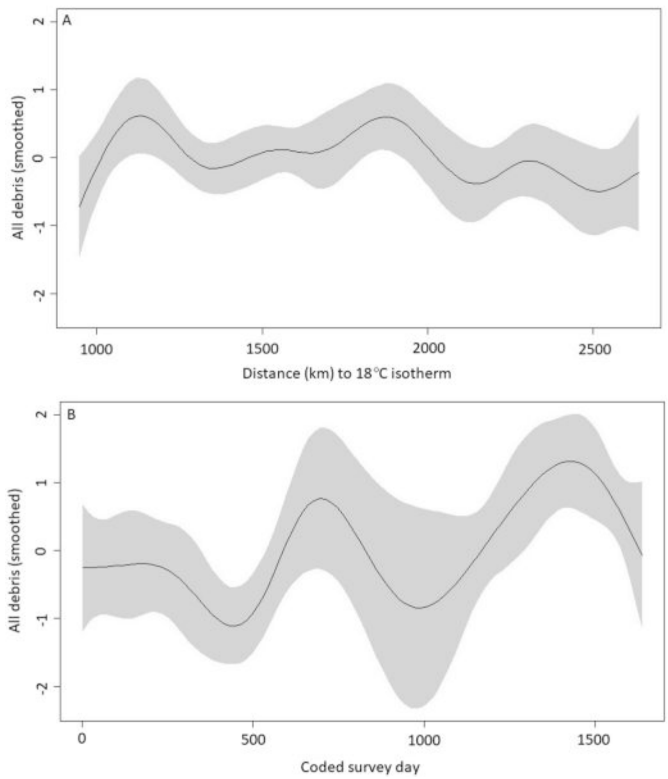

Fig. 8. Results of generalized additive model showing the significant non-linear relationships of all debris and (A) distance to 18 °C isotherm and (B) survey date for debris collected within coastal waters of Maui County, Hawaii between 2013 and 2017.
Note: Survey date is coded so that 1 = April 6, 2013 and 1634 = October 12, 2017.

(Donohue et al., 2001; Ribic et al., 2012). The proportion of general-source debris recorded in this study is slightly higher than the 30–40% recorded in other shoreline surveys in Hawaii (Ribic et al., 2012). This is likely attributed to the addition of items to the general-source category for this study, not included in the original designation by Ribic et al. (2012). Furthermore, the high proportion of unknown-source debris and the observed biofouling suggests that few items were littered into the environment recently, and thus could have come from very distant locations.

The subset of samples analyzed in 2017 suggests that only low-density floating debris were observed in the Maui County region. The high proportion of severely weathered debris suggests that few items were littered into the environment recently and most come from distant sources. These results are congruent with previous studies that found PE and PP to dominate sea surface plastic marine debris in the North Pacific (Brandon et al., 2016), North Atlantic (ter Halle et al., 2016), Indian Ocean (Syakti et al., 2017), Mediterranean Sea (Pedrotti et al., 2016), Ross Sea (Cincinelli et al., 2017), coastal Southern Malaysia (Ng and Obbard, 2006), and on beaches of Kauai, Hawaii (Cooper and Corcoran 2010). Any debris made of PET, PVC, PS, nylon, and other denser polymers entering Hawaiian waters from local sources would sink and the collection of only visible floating debris for this study explains the near absence of this type of polymer in the analysis. As such, a large amount of the marine debris is likely going undetected, as it is sinking through the water column or on the sea floor. The one piece of PET plastic collected and analyzed during the survey would have naturally sunk, but the item was a bottle that still had air inside, which kept it afloat until sample collection. Had it filled with water, it would have certainly sank and been deposited on the sea floor.

As has been shown in previous work by Ribic et al. (2010, 2011, 2012), the complex relationships of debris accumulation and varying drivers leads to temporal patterns of debris accumulation. Blickley et al. (2016) found debris accumulation on Maui's beaches fluctuated on a monthly and daily basis and resuspension of debris was related to wind, tides and wave height. Ocean based phenomena such as ENSO events, as well as proximity to the STCZ, as indicated by the 18 °C isotherm (Pichel et al., 2007), did have a significant impact on overall debris quantities and unknown-source debris observed in this study. Although not assessed in this study, there could be a delayed pulse of debris accumulation occurring after strong El Nino years, explaining the significance positive debris counts during non ENSO event months observed in this study. For example, the 2016 moderate to strong El Nino could have caused the high accumulation event observed in 2017, and not be predicted by ENSO months or proximity to the STCZ used in our models due to an untested lag effect. This movement of the STCZ further south and closer to Hawaii could have resulted in deposition of high amounts of debris into Hawaii's dynamic coastal waters. This may have caused the increase in debris accumulation observed in 2017, as the debris was subject to movement through this dynamic system. The role of ENSO events and the STCZ on coastal debris accumulation warrants additional research to help understand the potential connection to high accumulation events.

Significant variables for all debris sources were a mix of local and large scale phenomena, suggesting a complex process of drivers, mostly relating to ocean based variables, are responsible for the observed variations in debris quantities within Maui County. There were five variables identified as significant drivers of ocean-based debris, suggesting multiple factors lead to the accumulation of ocean-based debris within Maui County. The low R^2 value suggests other untested factors are contributing to ocean-based debris fluctuations. The increase in ocean-based debris count with temperature could be contributed to the proximity of the STCZ to Maui, which is closer during colder periods and is known to concentrate debris (Pichel et al., 2007). This is further supported by the significance of the 18 °C isotherm in increasing and decreasing all debris counts regardless of source, suggesting that observed debris likely originate outside the Hawaiian Islands. Temperature could also serve as a proxy for various oceanic processes (Ryan et al., 2009) that were not specifically tested here. The large fluctuations in ocean-based debris over time observed between 2015 and 2016 aligned with one of the strongest El Niño events observed since 1950 (ENSO, 2016). The absence of the ENSO variable from the lowest AIC model for the ocean-based debris likely resulted from debris that arrived via the ocean being classified as unknown-source due to inability to identify the source. Additionally, interaction effects were not tested and only considering the ENSO variable on its own could further explain the absence from this model. This is further supported by the inclusion of the ENSO variable in the model looking at all debris regardless of source category.

The general increase in ocean-based debris from 100 to 250° corresponds to wind coming from a direction unobstructed by any of the four islands, with the peak of 200–250° (from Southwest) representing the least obstructed area between Kahoolawe and Lanai.

The increase in sea level pressure read at the buoy southwest of the study area is indicative of a shift in the high pressure ridge over the islands, which causes a stalling of the prevailing Northeast trade winds common to the Hawaiian Islands (Garza et al., 2012). The observed increase in ocean-based debris quantities with increasing sea level pressure suggests this stalling of trade winds slows the transport of ocean-based debris out of the study area. This is further supported by the significant increase in debris observed during non-ENSO/LNSO months for all debris, as this is when a slowing of the trade winds is expected.

The general decrease in land-based debris with water temperature observed could be attributed to seasonal beach use by residents and tourists, not detected using visitor count categories. Sea surface temperatures are hottest in September and October (National Data Buoy

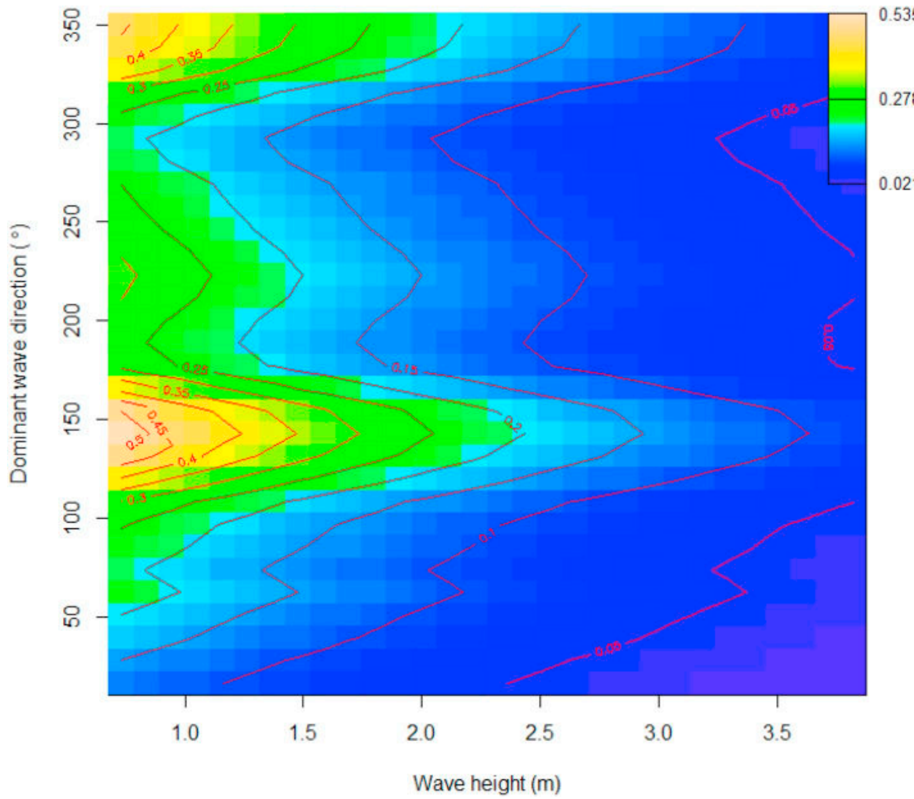

Fig. 9. Results of generalized additive model showing the significant relationship of the interaction between wave height and direction on all debris counts collected within coastal waters of Maui County, Hawaii between 2013 and 2017.

Center 2018a), which corresponds with the lowest monthly average visitor days for the island of Maui (Hawaii Tourism Authority, 2018) and could explain the reduction in debris counts from 25 to 27 °C. Temperatures in the range of 24–25 °C correspond to the peak tourism months of December to March which may explain the peak observed in land-based debris at these temperatures. The authors believe water temperature in Hawaii could be an inverse measure to indicate the number of beach users. However, further research is needed to confirm these trends and to assess if tourists contribute more or less marine debris than local residents. Population levels have been shown to impact debris deposition (Thiel et al., 2011) and variations in visitors to Maui may impact the amount of debris observed through direct deposition and/or deposition via transport systems such as streams to the ocean system (Ribic et al., 2012).

Wind is a primary driver of debris transport over land and deposition into coastal waters (Blickley et al., 2016). The initial trend of high land-based debris deposition with low wind speeds could relate to the number of beach users because calm, windless days are favored for beach activities, which are common throughout Maui. The variability observed in land-based debris deposition with wind speed is not surprising as the amount and rate of land-based debris collection in this study was likely the result of complex drivers that vary with beach site. Blickley et al. (2016) showed that land-based accumulation on beaches was mostly influenced by wind, which was also the most significant term for accumulation of land-based debris in Maui's nearshore waters.

General-source debris represented the largest proportion of data collected in this study and can be affected by land-based or ocean-based processes (Barnes et al., 2009; Ribic et al. 2012). Survey date was the only variable that was significant in the general-source model and common with the lowest AIC model for ocean-based debris. This suggests that general-source debris accumulation in Maui County has a temporal component, which may be linked to ocean processes as suggested in Ribic et al. (2012).

The decreasing non-linear trend in general-source debris counts from 2013 to 2017 is worth noting as it corresponds with increasing linear estimates of yearly debris counts. Although the yearly estimates

Table 3
Results of top generalized additive model used for determining the linear and nonlinear relationships between ocean-based debris counts and variables, based on data collected within the coastal waters of Maui County, Hawaii between 2013 and 2017.

Factor		edf[a]	F-value	p-Value	R^2	Dev. expl.
Ocean-based nonlinear	s(wind direction)	7.86	2.41	0.02	0.14	43.6%
	s(air temp)	3.28	5.70	< 0.0001		
	s(survey date)	7.27	3.21	< 0.001		

Factor		Estimate	t-Value	p-Value	R^2	Dev. expl.
Ocean-based linear	Wave height	0.09	1.37	0.17	0.14	43.6%
	Dominant wave period	−0.06	−2.13	0.03		
	Sea level pressure	0.13	3.26	< 0.001		

[a] edf is the estimated degrees of freedom accounting for the smoothing function.

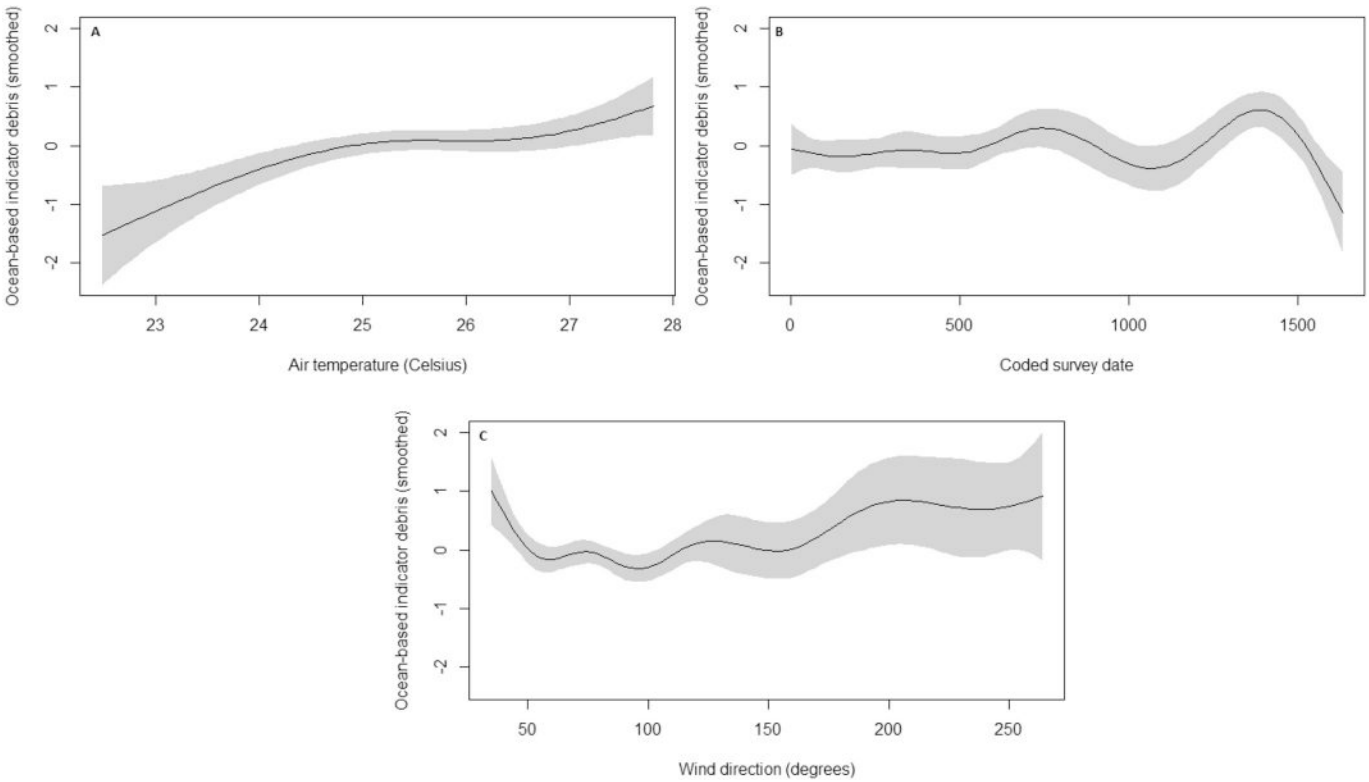

Fig. 10. Results of generalized additive model showing the significant non-linear relationships of ocean-based debris and (A) air temperature, (B) survey date, and (C) wind direction for debris documented within coastal waters of Maui County, Hawaii between 2013 and 2017.
Note: Survey date is coded so that 1 = April 6, 2013 and 1634 = October 12, 2017. Fig. 10C represents trends over recorded over the dominant wind direction, which ranged from 35 to 264° throughout the survey period.

are not significant, these results would suggest a strong temporal component that varies on a daily and yearly basis and is likely a proxy for a process not tested in our models.

There were six variables identified as significant drivers of unknown-source debris, all relating to ocean-based environmental variables suggesting the majority of debris in this category has been floating in the ocean for prolonged periods of time. This is further supported by the fragmented nature of debris in this category, likely being broken down from sun, wind, and wave action. The variation in unknown-source debris counts with water temperature is likely the result of the movement of the STCZ to Maui, which is known to concentrate debris (Pichel et al., 2007). The high significance counts of unknown-debris during non ENSO event months is similar to what was observed for all debris and likely is the result of a similar process and a delayed pulse after a strong ENSO month. The increasing trend of unknown-debris counts with increasing wind speed and the decreasing trend of unknown-debris counts with increasing peak gusts is likely attributed to the topography of the Maui Nui region. Further, it suggests unknown-debris is largely influenced by wind driven currents and waves with increasing wind speed increasing accumulation and high gusts moving debris either onshore, or beyond the study region.

The use of an unknown-source category represents an important addition to the categories presented by Ribic et al. (2012), for the Hawaii region as it represents a large portion of the observed debris. The expansion of categories proposed by Ribic et al. (2012) to include an unknown-source of debris fragments is further strengthened by the fact that plastic fragments make up an estimated 96% of the plastics found in the North Pacific (Robards et al., 1997). As such, identifying significant drivers for this category will contribute to a better understanding of debris accumulation in the North Pacific.

To mitigate the problem of marine debris an understanding of how it gets into our environment is required. To the best of the author's knowledge, this is the first published study in Hawaii to conduct systematic ocean surveys as a method of quantifying marine debris and, as

Table 4
Results of top generalized additive model used for determining the linear and nonlinear relationships between land-based debris counts and variables, based on data collected within the coastal waters of Maui County, Hawaii between 2013 and 2017.

Factor		edf[a]	F-value	p-Value	R^2	Dev. expl.
Land-based nonlinear	s(wave height)	1.82	0.85	0.47	0.32	57.1%
	s(average wave period)	2.80	2.310	0.07		
	s(water temperature)	2.19	3.71	0.02		
	s(average wind speed)	7.02	2.89	0.01		
Factor		**Estimate**	**t-Value**	**p-Value**	**R^2**	**Dev. expl.**
Land-based linear	Dominant wave direction	−0.01	−1.33	0.19	0.32	57.1%

[a] edf is the estimated degrees of freedom accounting for the smoothing function.

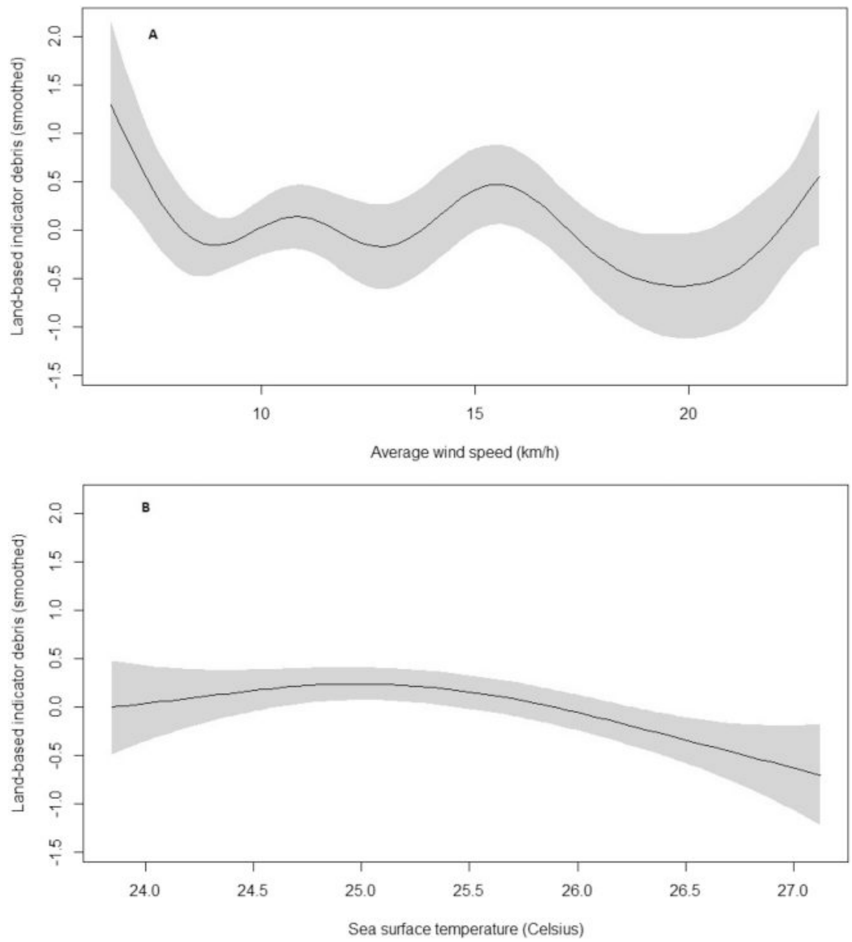

Fig. 11. Results of generalized additive model showing the significant non-linear relationships of land-based debris and (A) wind speed and (B) sea surface temperature for debris documented within coastal waters of Maui County, Hawaii between 2013 and 2017.

such, provides valuable baseline information on the sources and accumulation patterns of pollution at the sea surface in this region. Removal efforts are useful in getting debris out of the environment, but quantifying the types, sources, and amounts of debris is essential to stopping this problem at the source. Systematic research is needed at the regional level because each area will have its own unique drivers and trends. Citizen science programs, such as Pacific Whale Foundation's Coastal Marine Debris Monitoring Program, can serve as a low cost method of obtaining data so researchers can monitor debris types and loads. Baseline data are important to obtain so that trends can be detected and these data are crucial for managers and lawmakers to implement informed, scientifically-backed policies and mitigation measures.

Disclaimer: Certain commercial equipment, instruments, or materials are identified in this paper to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Table 5
Results of top generalized additive model used for determining the linear and nonlinear relationships between general-source debris counts and variables, based on data collected within the coastal waters of Maui County, Hawaii between 2013 and 2017.

Factor		edf[a]	F-value	p-Value	R^2	Dev. expl.
General nonlinear	s(month)	6.83	1.66	0.12	0.30	43.1%
	s(survey date)	5.29	6.26	< 0.001		
	s(water temperature)	6.95	8.05	0.11		

Factor		Estimate	t-Value	p-Value	R^2	Dev. expl.
General linear	Year 2014	3.95	1.49	0.14	0.30	43.1%
	Year 2015	9.52	1.80	0.07		
	Year 2016	14.41	1.83	0.07		
	Year 2017	19.48	1.85	0.06		

[a] edf is the estimated degrees of freedom accounting for the smoothing function.

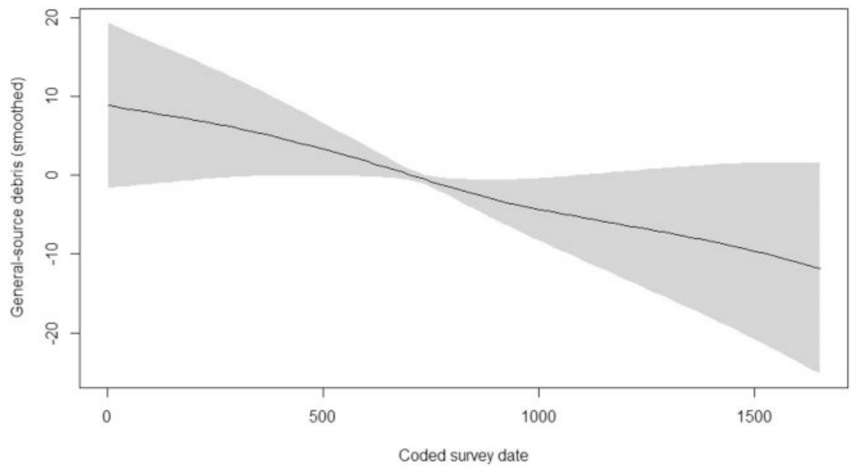

Fig. 12. Results of generalized additive model showing the significant non-linear relationships of general-source debris and survey date for debris collected within coastal waters of Maui County, Hawaii between 2013 and 2017.
Note: Survey date is coded so that 1 = April 6, 2013 and 1634 = October 12, 2017.

Table 6
Results of top generalized additive model used for determining the linear and nonlinear relationships between unknown-source debris counts and variables, based on data collected within the coastal waters of Maui County, Hawaii between 2013 and 2017.

Factor		edf[a]	F-value	p-Value	R^2	Dev. expl.
Fragments nonlinear	s(average wave period)	1.27	1.51	0.17	0.45	51.5%
	s(water temperature)	4.41	3.92	< 0.001		

Factor		Estimate	t-Value	p-Value	R^2	Dev. expl.
Fragments linear	Survey date	0.001	7.37	< 0.0001	0.45	51.5%
	La Nina Oscillation	0.682	2.33	< 0.01		
	No Oscillation	1.01	4.81	< 0.0001		
	Average wind speed	1.46	2.36	< 0.01		
	Peak gusts	−1.32	−2.44	< 0.01		

[a] edf is the estimated degrees of freedom accounting for the smoothing function.

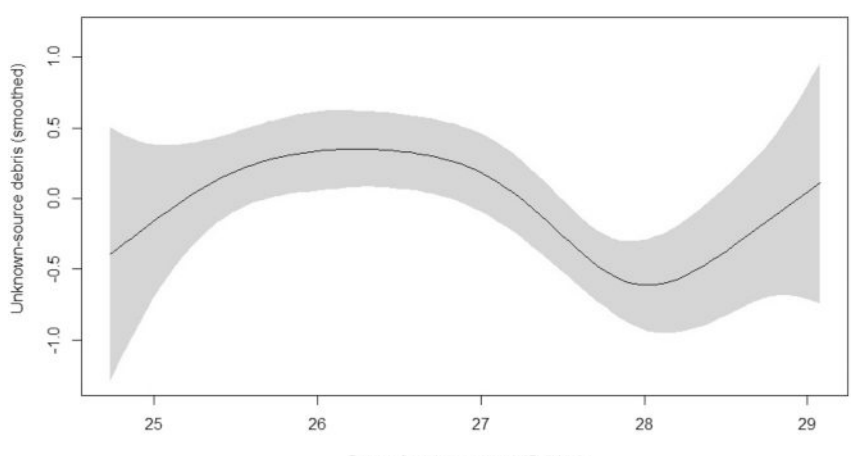

Fig. 13. Results of generalized additive model showing the significant non-linear relationships of unknown-source debris and water temperature for debris documented within coastal waters of Maui County, Hawaii between 2013 and 2017.
Note: Survey date is coded so that 1 = April 6, 2013 and 1634 = October 12, 2017.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2018.11.026.

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