Marine Pollution Bulletin 105 (2016) 292–298

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Trends and drivers of debris accumulation on Maui shorelines: Implications for local mitigation strategies

Lauren C. Blickley *, Jens J. Currie, Gregory D. Kaufman

Pacific Whale Foundation, 300 Ma'alaea Road, Suite 211, Wailuku, Maui, HI 96793, USA

ARTICLE INFO

Article history:
Received 18 August 2015
Received in revised form 29 December 2015
Accepted 1 February 2016
Available online 28 February 2016

Keywords:
Marine debris
Hawaii
Accumulation rates
Policy
Plastic pollution

ABSTRACT

Marine debris, particularly plastic, is an identified concern for coastal areas and is known to accumulate in large quantities in the North Pacific. Here we present results from the first study to quantify and compare the types and amounts of marine debris on Maui shorelines. Surveys were conducted monthly between May 2013 and December 2014, with additional daily surveys conducted on Maui's north shore during January 2015. Debris accumulation rates, loads, and sources varied between sites, with plastics being the most prevalent type of debris at all sites. Large debris loads on windward shores were attributed to the influence of the North Pacific Subtropical Gyre and northerly trade winds. Daily surveys resulted in a significantly higher rate of debris deposition than monthly surveys. The efficacy of local policy in debris mitigation showed promise, but was dependent upon the level of enforcement and consumer responsibility.

1. Introduction

Marine debris is a serious concern for coastal communities across the world. Not only does marine debris pose considerable threat to marine life, biodiversity, and ecosystems, but additionally impacts human health, safety, and local and national economies (Sheavly and Register, 2007; Gregory, 2009; Secretariat of the Convention on Biological Diversity (SCBD), 2012). Marine debris can further translate into loss of tourism revenue and recreation value, as well as affect coastal industries such as shipping and commercial fishing (Sheavly and Register, 2007; SCBD, 2012). Overall, plastics are considered the most common type of marine debris (Coe and Rogers, 1997; Derraik, 2002), with recent studies estimating the amount of plastic currently in the ocean at 5.25 trillion particles (Eriksen et al., 2014). Buoyant, lightweight, and slow to degrade, plastics have the ability to travel thousands of miles on ocean currents and can be deposited even on remote, uninhabited shorelines (Slip and Burton, 1991; Barnes, 2002; Morishige et al., 2007).

In the North Pacific Ocean, significant amounts of plastics and other debris have been discovered to accumulate in zones of regional surface current convergence that result from the clockwise rotation of the North Pacific Subtropical Gyre (STG) (Kubota, 1994; U.S. EPA, 2011; Howell et al., 2012; Law et al., 2014). Colloquially termed "garbage patches", these areas have been identified in both the Eastern and Western North Pacific Ocean (Moore et al., 2001; Howell et al., 2012; Law et al., 2014). The Eastern and Western garbage patches themselves are linked by the Subtropical Convergence Zone (STCZ), a band of surface layer convergence that is located at the northern terminus of the STG (Pichel et al., 2007; U.S. EPA, 2011; Howell et al., 2012). Along with the garbage patches, the STCZ is known to concentrate marine debris (Pichel et al., 2007; U.S. EPA, 2011). In addition to surface currents, accumulation of debris on beaches is strongly influenced by wind speed and direction (Walker et al., 2006; Garcon et al., 2009; Eriksson et al., 2013).

The Hawaiian Archipelago is found within the STG and in close proximity to the STCZ, which likely contributes to the large amount of marine debris documented along Hawaiian shorelines (Ribic et al., 2012a). To date, the majority of marine debris accumulation studies in the Archipelago have focused on sites in the Northwestern Hawaiian Islands (NWHI), a string of uninhabited atolls stretching 1500 km northwest of the Main Hawaiian Islands (MHI) (Donohue et al., 2001; Henderson, 2001; Boland and Donohue, 2003; Dameron et al., 2007; Morishige et al., 2007; Ebbesmeyer et al., 2012; Ribic et al., 2012b). Despite the lack of large-scale human development, thousands of pounds of ocean-based marine debris have been removed from NWHI coastal areas (Donohue et al., 2001; Donohue, 2003).

Although fewer studies have been conducted on marine debris in the MHI, results indicate that debris accumulation is an issue (McDermid and McMullen, 2004; Corcoran et al., 2009; Cooper and Corcoran, 2010; Ribic et al., 2012a). Long-term data sets from O'ahu demonstrate that Hawaiian shorelines experience higher debris loads than coastal areas along the U.S. Pacific Coast, particularly ocean-based debris such as fishing nets and floats/buoys (Ribic et al., 2012a). Variation in debris loads on O'ahu were further linked to environmental drivers, particularly fluctuations in the regional El Nino Southern Oscillation cycle (ENSO) (Ribic et al., 2012a). Small-plastic debris has also been recorded on remote beaches in both the NWHI and MHI

* Corresponding author.
E-mail address: LCBlickley@gmail.com (L.C. Blickley).

http://dx.doi.org/10.1016/j.marpolbul.2016.02.007
0025-326X/

(McDermid and McMullen, 2004). Although studies have demonstrated that local debris inputs can contribute to local debris accumulation in Hawai'i (Carson et al., 2013), there is little understanding of how local environmental conditions influence accumulation rates and debris loads in the MHI. In addition, the impact of sampling interval on estimated accumulation rate remains to be explored, not only in the MHI but on shorelines worldwide (Ryan et al., 2009).

This is the first study to quantify the types and amounts of marine debris found on Maui shorelines and the main objectives were: 1) to identify localized environmental factors that influence marine debris accumulation on Maui beaches; 2) investigate the effects of temporal scale on accumulation rates; 3) characterize the type of marine debris most prevalent on Maui beaches; 4) evaluate the effectiveness of local marine debris policy and programs in Maui County. It was hypothesized that a higher debris load and rate of debris accumulation would occur at sites situated along Maui's windward coastline, due to the shoreline's orientation to trade winds and/or large wave events.

2. Methods

2.1. Site selection

Maui's climate is dominated by northeasterly trade winds experienced approximately 80% of the year, with stronger more consistent winds during the summer months (Sanderson, 1993). To account for environmental variations across the island, three study sites were chosen to represent shorelines from three of the four main geographical areas of the island: Site 1 (Pu'unoa Beach) (20.88421; −156.68681) on the West Shore, Site 2 (Po'olenalena Beach) (20.66310; −156.44164) on the South shore and Site 3 (Lower Waiehu Beach) (20.924177; −156.493389) on the North shore (Fig. 1). Study constraints prohibited the ability to select an East Maui site. Survey sites were chosen according to the criteria of the NOAA Marine Debris Shoreline Survey Field Guide (Opfer et al., 2012). Furthermore, sites were chosen that did not immediately front resorts, and best attempts were made to survey beaches that were less impacted by human traffic.

2.2. Site surveys

Monthly and daily site surveys were conducted following the accumulation survey protocol outlined in the NOAA Marine Debris Shoreline Survey Field Guide (Opfer et al., 2012). Prior to initial surveys, debris from each site was collected and removed to develop a baseline for accumulation. After the initial cleanup, all collected debris items were sorted and classified according to the following general categories: plastic, rubber, processed lumber, clothing/fabric, metal, large debris (>30 cm) which were further broken down into 66 subcategories. Only debris items measuring greater than 2.5 cm were collected. To determine the origin of debris, items were divided into three indicator debris categories based on their likely source. Categories were based on Ribic et al. (2012a) and are presented in Table 1.

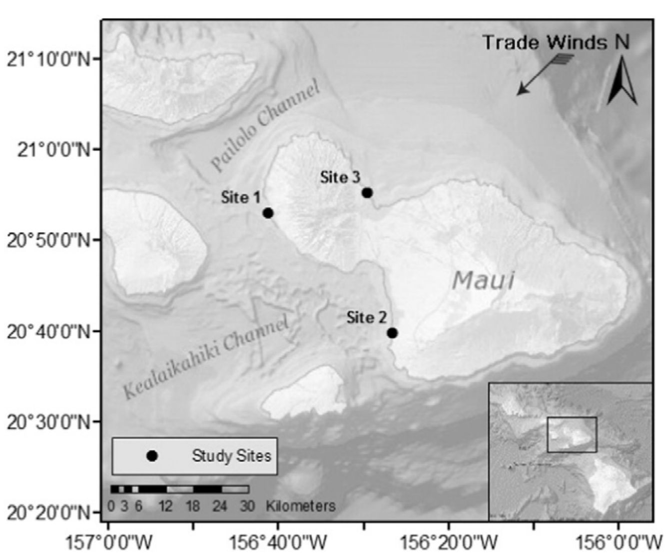

Fig. 1. Map showing the direction of prevailing trade winds and location of the three study sites on Maui. Site 1 = Pu'unoa Beach; Site 2 = Po'olenalena Beach; Site 3 = Lower Waiehu Beach.

2.2.1. Monthly accumulation

Monthly surveys took place at each site once every 28 days (±3 days) within ±30 min of low tide. Surveys were conducted within an established 100 m transect. Date, time, weather conditions, width of shoreline, and presence of storm activity within the past week were recorded for each survey. Each transect was traversed perpendicular to the water in 5 m increments, and covered the entire beach width from the water's edge to the vegetation line. Beach slope for each site was calculated using methods presented in Emery (1961). Surveys were conducted on a monthly basis from May 2013 through August 2014 for both Site 1 and Site 2 (17 total surveys) and from October 2013 through December 2014 for Site 3 (16 total surveys).

2.2.2. Daily accumulation

Site 3 was selected for additional daily accumulation surveys due to the large debris loads observed during monthly surveys. Accumulation surveys followed the same protocol as monthly surveys and were conducted daily for 28 consecutive days at Site 3 from January 2, 2015 through January 29, 2015.

2.3. Analysis

2.3.1. Monthly accumulation

A total of three monthly indices were calculated for each survey site to explain potential debris accumulation and retention. To summarize monthly wind speed and direction, a Relative Exposure Index (REI) was modified from Walker et al. (2006). A total of 8 wind directions determined by beach orientation were analyzed per site, each encompassing a total of 180°:

$$REI = \sum_{i=1}^{8} \frac{V_i P_i F_i}{100}$$

where V_i is the mean monthly wind speed (km h^{-1}) for wind directions categorized in 45° increments; P_i is the percent frequency from which the wind blew within each increment; and F_i is the fetch (USACERS, 1977) distance (km). Fetch lengths greater than or equal to 100 km were all set to 100 km and assumed to represent

Table 1
Indicator debris items classified by source category, as adapted from Ribic et al., 2012a.

Ocean-based	Land-based	General-source
Nylon rope/net fragments	Cigarette filters/cigars	Beverage bottles
Buoys/floats	Straws	Plastic bags
Fishing lures/line	Balloons	Packing straps
Spools	Fireworks	Bottle/container caps
Light sticks	Golf balls	Other jugs/containers
Oyster spacer tubes (large and small)*	Golf tees	
Hagfish traps*	Syringes	
	Personal care products	
	Flip-flops/slippers	
	Tires	
	Food wrappers	
	Clothing/shoes	

* Used only for analysis of daily accumulation debris.

unlimited fetch in the ith direction (Puotinen, 2005; Garcon et al., 2009).

To summarize monthly tide and wave activity, a Relative Tidal Range (RTR) was modified from Short (1996) and an Intertidal Area (IA) adapted from McLachlan and Dorvlo (2005):

$$RTR = \frac{H_t}{H_w}$$

$$IA = \frac{H_t}{S}$$

where H_t is mean monthly tide height in meters (m), H_w is the mean monthly wave height (m) and S is the beach slope. The initial model used to investigate debris per unit effort (DPUE) (count/100 m) included explanatory variables REI, RTR and IA, and non-significant variables that did not improve model fit were subsequently dropped.

Tide and wave height data for each site were extracted from the Center for Operational Oceanographic Products and Services (2015). Wind speed and directions were extracted for each site using the weatherData package (Narasimhan, 2014) in R.

To evaluate the efficacy of a recently introduced tobacco free beaches policy, which prohibits tobacco use on Maui beaches (County of Maui, 2014), the monthly accumulation of cigarette filter debris before and after the April 22, 2014 ban were compared. Owing to small sample size, a two sample equal variance t-test was used to determine if the mean monthly cigarette counts differed significantly before and after the ban.

2.3.2. Daily accumulation

The major daily beach forces of tide and wind (Eriksson et al., 2013) were recorded during debris collection to investigate environmental effects. Mean and max tide heights (m) as well as mean wave height (m), period (sec), and direction were obtained from Pacific Islands Ocean Observing System (PacIOOS) waverider buoy (Coastal Data Information Program, 2015). The buoy was located at N21.018°, W156.425°, approximately 10 km from the study site in 193 m of water. Daily wind data, including average wind speed (mph), highest wind speed (mph), and wind direction, were obtained from the National Climatic Data Center's (NCDC) automated weather observing system station (NCDC, 2015).

2.3.3. Model fitting

Generalized Linear Models (GLMs) were used to model the relationship between debris accumulation and environmental variables (McCullagh and Nelder, 1989):

$$y_i = \beta_0 + \beta x_i + \varepsilon_i$$

where $y_i, i = 1,\ldots,n$ is the response variable modeled as a linear function of the explanatory variable βx_i; β_0 is the intercept; and ε_i is the random error. Two different data sets were used in the GLM analysis, one for monthly debris accumulation at 3 sites and another at a selected site for daily accumulation. The response variable for the monthly analysis was a count of debris accumulation over ~30 days per 100 m of shoreline. The explanatory variables were all based on monthly summaries averaged over the 30 days prior to sample date and included REI, RTR and IA. The response variable for the daily analysis was a count of debris items collected per 100 m of shoreline each day. The explanatory variables were all summarized by day and included mean and max wind speeds, prevailing wind direction treated as factor, mean and max tide height, mean swell height, mean swell period and prevailing swell direction (treated as a factor). Models were initially fit assuming a Poisson distribution with a logarithmic link function. A Quasi Poisson distribution was fit when data were over-dispersed.

All computations were completed using the "mgcv" package in R (Wood, 2011). Final model selection was based on minimizing the Akaike Information Criterion, AIC (Sakamoto et al., 1986). Multicollinearity among predictor variables was tested by calculating the correlation coefficient and variables showing significant correlation were dropped. To ensure proper model fit and adherence to assumptions, model residuals were graphed and checked for violations (Augustin et al., 2012).

3. Results

3.1. Monthly accumulation

A total of 17 surveys were conducted at Sites 1 (May 16, 2013–August 29, 2014) and 2 (May 10, 2013–August 19, 2014), and a total of 16 surveys were conducted at Site 3 (October 4, 2013–December 22, 2014). Site 3 had the highest rate of debris accumulation per month (197.5 debris items/month) compared to Site 1 (96.76 debris items/month) and Site 2 (25.35 debris items/month). Surveys coincided between sites from October 2013 through August 2014. Due to the 28 day (±3 days) sampling interval, sites were sometimes sampled twice during a single month. Surveying overlap between sites is therefore shown graphically from October 2013–September 2014. Debris accumulation did not appear to show trends across months or seasons, and peak debris loads at each site did not overlap (Fig. 2).

Cumulative debris counts over the twelve month period (October 2013–September 2014) varied notably between sites (Fig. 3). The total number of debris items collected at Site 3 within this period (2446) was nearly twice the amount of debris collected at Site 1 (1232) and over nine times the amount collected at Site 2 (263) (Fig. 3).

Debris composition was similar among beaches, with plastic items being the most prevalent type of debris collected at each site: Site 1 (80%); Site 2 (71%); Site 3 (94%). Site 1 debris, however, was characterized by a significantly larger amount of cigarette filters (746) than either Site 2 (95) or Site 3 (102), with cigarette filters alone constituting 45% of Site 1's total debris load. In addition, Site 3 had larger amounts of hard, plastic fragments (1859) than either Site 1 (197) or Site 2 (60).

3.1.1. Site 1

The Relative Exposure Index (REI) at Site 1 averaged ~0.126 from June to November, after which it increased threefold to ~0.418 from December to May. Relative Tidal Range (RTR) and Intertidal Area (IA) showed no seasonal trends and had an average of 1.177 and 0.056 respectively. Results from General Linear Model (GLM) analysis showed a significant relationship between monthly debris accumulation and IA (Table 2).

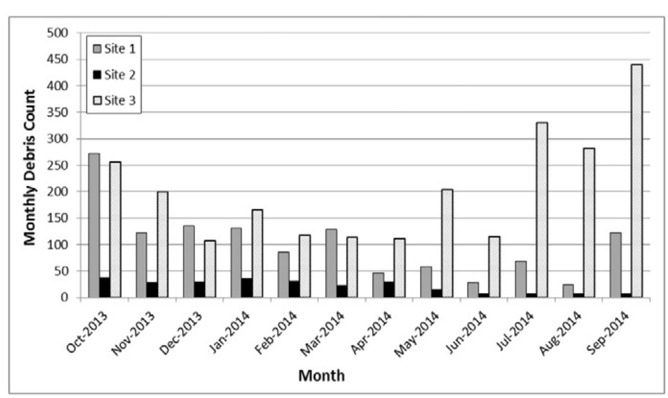

Fig. 2. Comparison of monthly debris counts at all sampling sites from October 2013 through September 2014. Note: Month labels represent date range within ±10 days of the last day of each month.

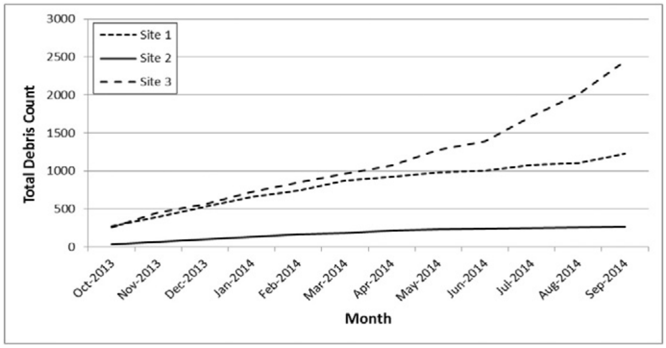

Fig. 3. Cumulative debris counts collected at each site over a 12 month period (October 2013–September 2014). Note: Month labels represent date range within ±10 days of the last day of each month.

3.1.2. Site 2

The REI for Site 2 showed a clear increasing trend from April to August, peaking at 4.44. The lowest REI, of 2.54, was observed in February. RTR and IA showed no seasonal trends and ranged from 0.55–3.47 and 0.11–0.13 respectively. The GLM analysis on monthly debris accumulation found all three indexes to be significant (Table 3), with the most signification term being RTR.

3.1.3. Site 3

REI ranged from 6.2 (March) to 13.5 (August) with no clear seasonal trends. Site 3 experienced higher RTR from May to November (RTR ~ 0.38) and lower values from December to April (RTR ~ 0.24). Similar trends were observed for IA with a max of 0.06 occurring in November and a minimum of 0.05 occurring in May. None of the calculated indexes were found to significantly impact total monthly count.

3.1.4. Indicator debris

The total number of indicator debris items varied across sites. Site 1 had over twice as many indicator debris items (949) than Site 3 (551), and more than twelve times the amount as Site 2 (114). The increased number of indicator debris items at Site 1 is attributed to the significantly larger number of cigarette filters found at Site 1 as compared to Sites 2 and 3. Land-based debris items represented the highest proportion of debris items for both Site 1 (89%) and Site 2 (86%) (Fig. 4A and B). In contrast, Site 3 indicator debris was primarily ocean-based (54%), followed by land-based (26%) and general-source (20%) (Fig. 4C).

3.1.5. Tobacco free beaches policy

Mean monthly cigarette filter counts were not significantly different for Site 1: $t(15) = 0.38$, $p = 0.71$ and Sites 3: $t(15) = -0.65$, $p = 0.52$ before and after the county-wide ban on tobacco use at Maui beaches. Site 2 showed a significant decrease in mean monthly cigarette count ($t(15) = 2.68$, $p = 0.02$) after the ban was imposed.

3.2. Daily accumulation

A total of 5864 pieces of debris were collected during daily sampling of Site 3. Plastics accounted for 88% of the total debris collected, followed by glass (7%). Together, rubber, processed lumber, clothing/fabric, and large debris accounted for less than 5% of the total debris count. Hard plastic fragments comprised the greatest proportion of plastic debris (53%), along with fishing/aquaculture/shipping-related debris (23.7%) and food/beverage debris (9.8%). Specific plastic debris types, besides plastic fragments, accounted for 2059 debris items, with the most common being nylon rope/net (911), bottle/container caps (375), oyster spacer tubes (157), straws (77), and fishing line (70).

Table 2
Summary results of Site 1 GLM monthly accumulation analysis for best fitting model (Quasi Poisson family, log link function).

	Estimate	SE	T	Pr(>|t|)
Intercept	−2.106	1.895	−1.111	0.290
RTR	−0.673	0.549	−1.224	0.246
REI	−0.156	0.123	−1.268	0.231
IA	124.802	30.985	4.028	0.002

Table 3
Summary results of Site 2 GLM monthly accumulation analysis for best fitting model (Quasi Poisson family, log link function).

	Estimate	SE	T	Pr(>|t|)
Intercept	0.091	2.00	0.045	0.964
RTR	0.473	0.130	3.649	0.002
REI	−0.583	0.222	−2.623	0.021
IA	38.723	16.272	2.380	0.033

3.2.1. Indicator debris

A total of 1930 indicator items were collected during daily surveys at Site 3. Ocean-based indicator items represented 62% of all indicator items, followed by general-source items at 24% and land-based sources at 14% (Fig. 5).

3.2.2. Model fitting

The GLM analysis on daily debris accumulation revealed mean wind speed to be the most significant explanatory variables with wind direction (NE) and tide height less significant, but still selected in the final model (Table 4).

Model predictions based on mean tide heights and NE wind direction showed an increasing trend in debris accumulation with wind speeds. Model predictions based on mean wind speed and NE wind direction revealed a decreasing trend in debris accumulation with increasing tide heights (Fig. 6).

3.3. Comparison of monthly and daily accumulation rates

Debris counts at Site 3 averaged 197.5 items per month when sampled once every 30 days over a 16 month period. Increasing the sampling frequency to once per day at the same site resulted in a significantly higher monthly debris count of 5864 items.

4. Discussion

Debris accumulation rates, loads, and sources varied between study sites due to differences in environmental factors including geographic location, wind speed, wind direction, and tidal height, all of which have been shown to influence debris deposition (Coe and Rogers, 1997; Ribic et al., 2012a). An evaluation of debris loads between survey sites showed that the orientation of shorelines to the Subtropical Convergence Zone (STCZ) and trade winds influence debris accumulation. Site 3, which is most exposed to prevailing trade winds and the STCZ, exhibited the largest debris loads and the greatest proportion of ocean-based debris when compared to Sites 1 and 2, both of which are located on Maui's leeward shoreline and were dominated by land-based debris. These results correspond with findings from debris accumulation studies in the Northwest Hawaiian Island (NWHI) (Donohue et al., 2001; Ribic et al., 2012b). The high proportion of ocean-based debris at Site 3, particularly debris items such as oyster spacer tubes and hagfish traps that originate beyond the Hawaiian Archipelago, further speaks to the regional nature of marine debris. Differences between debris composition in the NWHI and MHI nevertheless suggest the need to better understand the influence of additional drivers (e.g. localized currents) on debris deposition, as well as the behavior of varying debris items within the marine environment. Plastics were the most common

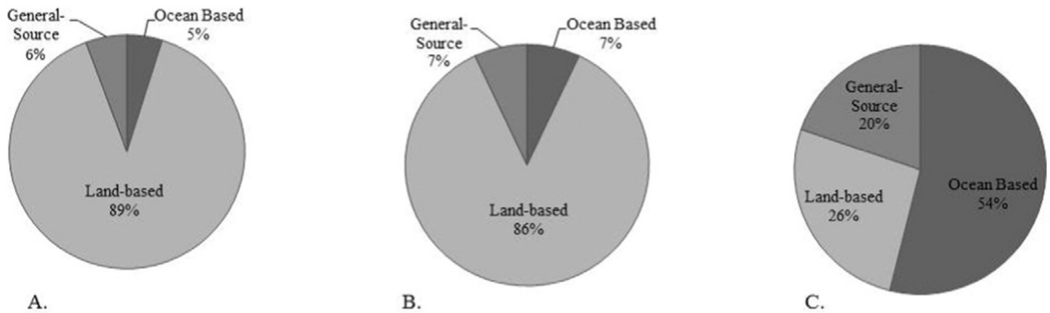

Fig. 4. Debris sources (%) as determined using indicator debris loads from Site 1 (A), Site 2 (B), and Site 3 (C).

debris item at each site, corroborating the prevalence of plastic debris in marine and coastal environments, as well as specifically within the MHI.

4.1. Monthly debris accumulation

Monthly debris surveys at Sites 1 and 2 were dominated by land-based debris, likely deposited by the movement of northeasterly trade winds across the island. This may explain the observed increase in debris deposition with decreased Relative Exposure Index (REI) at Site 1.

Previous debris accumulation studies have noted that the proximity of beaches to urban areas can influence debris loads (Ribic et al., 2012a; Carson et al., 2013; Leite et al., 2014). However despite its proximity to Maui's largest population center, Site 3 exhibited the least amount of land-based debris as compared to Sites 1 and 2. It is therefore likely that environmental variables, specifically trade winds, play a more significant role in debris deposition at the selected survey sites than proximity to urban areas, although debris deposition as it relates to local debris sources and sinks should be further explored.

Intertidal Area (IA) appears to influence debris accumulation through a combination of deposition of debris above the average tide height and removal of debris that is found below the high tide line. Increases in monthly IA, for example, were found to increase debris deposition at Sites 1 and 2, as higher tides deposited debris above the average tide line. The opposite trend was observed, however, during daily accumulation surveys at Site 3, where increased IA resulted in a decrease in debris deposition. These differences highlight the importance of temporal scale of sampling and the variation in results that are obtained when evaluating debris accumulation on a monthly versus daily basis (Smith and Markic, 2013).

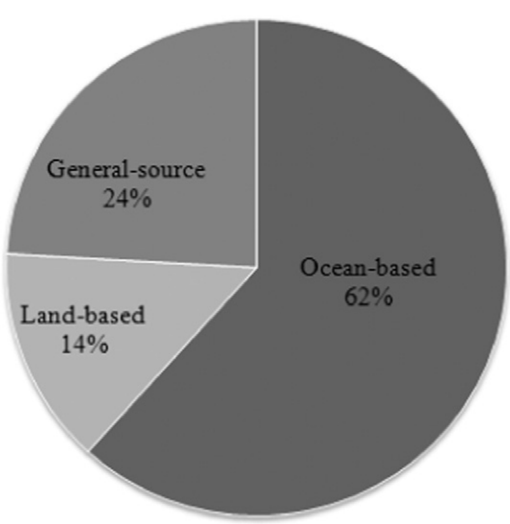

Fig. 5. Debris sources (%) as determined using indicator debris loads from daily accumulation surveys at Site 3.

Unlike Sites 1 and 2, none of the calculated indexes were found to significantly impact monthly debris loads at Site 3. This result is attributed to the frequent, large-scale changes in environmental conditions at Site 3, where northeasterly trade winds can vary daily from ~5 knots to ~30 knots. Drivers such as RTR and IA appear to average out over a monthly timeframe, as do the cumulative seasonal effects of large wave events and/or strong trade winds.

Debris accumulation did not exhibit seasonal trends at any site, despite the distinct seasonality of environmental variables such as large north swell events that occur in the winter and stronger, more consistent trade wind events that occur in the summer. Long-term accumulation studies conducted in the NWHI also found no link between debris deposition and seasonality, yet did find a positive relationship between debris deposition and El Niño events (Morishige et al., 2007). Additional studies have noted the seasonal migration of ocean fronts that tend to concentrate marine debris in the North Pacific, and suggest that shorelines in the Hawaiian Archipelago would experience higher debris loads during the winter (when fronts are closer to the islands) than in the summer (Pichel et al., 2007). It is likely, though, that seasonal variability has a more profound effect on debris loads in the NWHI than the MHI, as the NWHI are located in closer proximity to these fronts.

Further studies should evaluate the potential of seasonal debris trends in terms of increased sampling frequency, for example from monthly surveys to bi-monthly or weekly surveys, while also exploring the impact of decadal events such as El Niño and the seasonal migration of debris fronts.

4.2. Daily debris accumulation

Mean daily wind speed, direction, and tidal height were all determined to be significant factors when evaluating daily debris trends at Site 3. This supports the results presented in Eriksson et al. (2013), which identified wind and tide as the major drivers for daily debris accumulation. In this study, stronger winds appeared to transport a greater amount of debris from ocean areas with high debris concentration (such as the STCZ) to Maui's exposed shorelines, whereas higher

Table 4
Summary results of GLM daily accumulation analysis for best fitting model (Quasi Poisson family, log link function).

	Estimate	SE	T	Pr(>|t|)
Intercept	3.654	0.572	6.391	<0.001
Wind speed	0.207	0.044	4.649	<0.001
Wind direction (NE)	1.379	0.396	3.479	<0.01
Wind direction (NNE)	0.194	0.478	0.406	0.690
Wind direction (NW)	0.039	1.147	0.034	0.974
Wind direction (S)	−0.641	0.717	−0.894	0.383
Wind direction (SSW)	−1.143	0.685	−1.669	0.112
Wind direction (SW)	−0.245	1.196	−0.205	0.840
Wind direction (WSW)	−0.365	1.268	−0.288	0.777
Tide height	−4.120	1.843	−2.235	<0.01

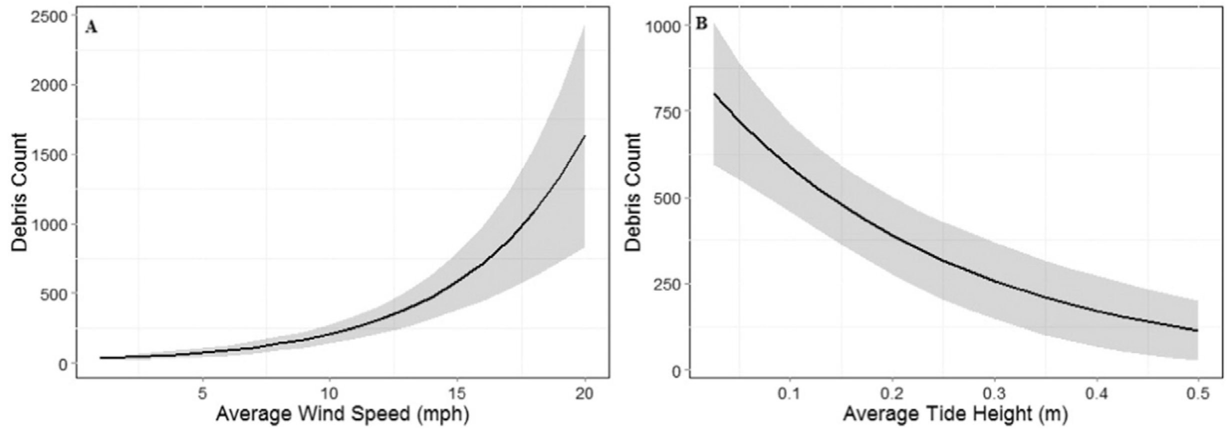

Fig. 6. Prediction of debris counts based on best fitting GLM for environmental covariates (A) wind speed and (B) tide height, where gray shaded areas represent confidence intervals.

tides redeposited debris back into the ocean, thereby decreasing debris deposition.

While Maui experienced large swell events at Site 3 during winter months, it is likely that daily sampling within this timeframe had minimal impact on data collection, and in fact may underrepresent debris loads. As wind, rather than tide height or wave height, was shown to be the most significant factor influencing daily debris accumulation at Site 3, authors postulate that large wave events may actually serve to remove debris from Maui shorelines, rather than deposit greater amounts of debris.

4.3. Impact of temporal sampling on accumulation rates

Monthly debris counts and proportion of ocean-based debris increased when sampling was undertaken on a daily versus monthly basis at Site 3. These findings support previous conclusions that debris turnover can occur rapidly and may be particularly influenced by variations in local conditions (Bowman et al., 1998; Ryan et al., 2009; Smith and Markic, 2013). The high turnover rate observed at Site 3 additionally supports the conclusion that tides serve to redeposit debris back into the ocean, and further reiterates the importance of daily sampling in not only assessing environmental variables, but also calculating at-sea debris loads.

4.4. Mitigation strategies

Results from this study indicate that local policies have varying success in mitigating marine debris. For example, although plastic grocery bags continue to rank as one of the top forms of litter in the state of Hawai'i (Ocean Conservancy, 2014), no plastic grocery bags were recorded in this study, a finding attributed to Maui's 2011 plastic bag ban. On the other hand, Maui's 2014 tobacco free beaches bill has had a variable impact on the amount of tobacco related debris items, with only Site 2 showing a significant decrease in cigarette filters after the bill's passage. The tobacco free beaches bill is inherently more difficult to implement as it relies heavily on local enforcement and a shift in social norms. This may explain the lack of reduced tobacco debris items found in this study. It is nevertheless recommended that the baseline cigarette filter loads established in this study be used to implement ongoing monitoring efforts, and that outreach and enforcement efforts target those beaches that are known to have a large amount of tobacco related debris (e.g. Site 1).

Some municipalities have moved to regulate marine debris as local level pollution in order to reduce the discharge of land-based debris, and the effectiveness of these types of efforts requires baseline debris loads (Ribic et al., 2012a). Community-based programs also show promise in terms of reducing local debris inputs. In 2013, a pilot fishing line recycling network was implemented at select Maui harbors for the disposal of discarded or unused fishing line (Pacific Whale Foundation, n.d.). Although bins were not located near study sites, and thus did not likely influence data collection, bins have been shown to be utilized by local fishers (pers. comm.), and expansion of the network could decrease fishing line debris on Maui beaches. Although the effectiveness of litter awareness campaigns were not evaluated in this study, it is likely that a reduction in local debris inputs will require a combination of targeted legislation, community-based waste reduction measures, and public outreach.

On a regional scale, previous studies suggest that North Pacific Ocean fisheries and ocean-based activities represent a primary input of debris to the NWHI (Donohue et al., 2001; Ribic et al., 2012b). From our results, it is clear that debris sources from the North Pacific also impact debris loads in the MHI. Elimination of these types of debris will require widespread action across hundreds of local municipalities, but efforts to address specific debris items, such as minimizing the loss of derelict fishing gear, will represent significant first steps.

5. Conclusions and recommendations

Results from this study demonstrate that a shoreline's orientation to the Subtropical Convergence Zone (STCZ) and local, environmental conditions (particularly wind speed and direction) drive debris deposition on Maui. The high incidence of ocean-based debris at sites exposed to the STCZ is further indication that debris originating from outside the Hawaiian Islands impacts local debris loads. Variations in debris deposition among sites are attributed to differences in both geographical location and local conditions between sites. Daily variation in environmental conditions showed to significantly impact debris accumulation rates. Comparisons between monthly and daily sampling reveal a high rate of debris turnover, attributed to extreme variation in local conditions, and also demonstrate the importance of sampling interval.

While not unattainable, solving the marine debris problem will require a holistic approach, one that combines debris removal projects, legislation, public outreach, and industry engagement with an enhanced understanding of marine debris and human behavior (Coe and Rogers, 1997; Sheavly and Register, 2007; Derraik, 2002). As knowledge gaps remain, it is recommended that long-term debris monitoring programs are established throughout the MHI to enhance our understanding of debris dynamics, monitor the efficacy of policy and local debris reduction efforts, and determine the fate and transport of common consumer debris items. Local mitigation actions should further be combined with regional efforts to address large debris item and those items (particularly plastics) that persist in the marine environment for extended periods of time.

Acknowledgments

The authors would like to thank Dr. Emmanuelle Martinez and Stephanie Stack for their insight and support in developing the initial scope of the project. A special thanks to Jill Wirt who assisted with debris collection and determining beach slope, as well as to Pacific Whale Foundation interns for their time spent quantifying debris items. This study was made possible through Pacific Whale Foundation.

References

Augustin, N.H., Sauleaub, E.-A., Wood, S.N., 2012. On quantile plots for generalized linear models. Comput. Stat. Data Anal. 56 (8), 2404–3409.
Barnes, D.K.A., 2002. Invasions by marine life on plastic debris. Nature 416, 808–809.
Boland, R.C., Donohue, M.J., 2003. Marine debris accumulation in the nearshore marine habitat of the endangered Hawaiian monk seal, *Monachus schauinslandi* 1991–2001. Mar. Pollut. Bull. 46, 1385–1394.
Bowman, D., Manor-Samsonov, N., Golik, A., 1998. Dynamics of litter pollution on Israeli Mediterranean beaches: a budgetary, litter flux approach. J. Coast. Res. 14, 418–432.
Carson, H.S., Lamson, M.R., Nakashima, D., Toloumu, D., Hafner, J., Maximenko, N., McDermid, K.J., 2013. Tracking the sources and sinks of local marine debris in Hawai'i. Mar. Environ. Res. 84, 76–83.
Center for Operational Oceanographic Products and Services, 2015,. Tides and Currents. U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration (Retrieved from http://tidesandcurrents.noaa.gov/).
Coastal Data Information Program, 2015. Scripps Institution of Oceanography. U.S., Army Corps of Engineers and the California Department of Boating and Waterways (Data accessed February 2015. <http://cdip.ucsd.edu/>).
Coe, J.M., Rogers, D. (Eds.), 1997. Marine Debris Sources, Impacts, and Solution. Springer-Verlag, New York.
Cooper, D.A., Corcoran, P.L., 2010. Effects of mechanical and chemical processes on the degradation of plastic beach debris on the island of Kauai, Hawaii. Mar. Pollut. Bull. 60, 650–654.
Corcoran, P.L., Biesginer, M.C., Grifi, M., 2009. Plastics and beaches: a degrading relationship. Mar. Pollut. Bull. 58, 80–84.
County of Maui, 2014. A bill for an ordinance amending Chapter 13.04, Maui County Code, prohibiting tobacco use and tobacco products in county parks. Retrieved from http://www.co.maui.hi.us/DocumentCenter/View/91715.
Dameron, O.J., Parke, M., Albins, M.A., Brainard, R., 2007. Marine debris accumulation in the Northwestern Hawaiian Islands: an examination of rates and processes. Mar. Pollut. Bull. 54, 423–433.
Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44, 842–852.
Donohue, M.J., 2003. How multiagency partnerships can successfully address large-scale pollution problems: a Hawaii case study. Mar. Pollut. Bull. 46, 700–702.
Donohue, M.J., Boland, R.C., Sramek, C.M., Antonelis, G.A., 2001. Derelict fishing gear in the Northwestern Hawaiian Islands: diving surveys and debris removal in 1999 confirm threat to coral reef ecosystems. Mar. Pollut. Bull. 42, 1301–1312.
Ebbesmeyer, C.C., Ingraham, W.J., Jones, J.A., Donohue, M.J., 2012. Marine debris from the Oregon Dungeness crab fishery recovered in the Northwestern Hawaiian Islands: identification and oceanic drift paths. Mar. Pollut. Bull. 65, 69–75.
Emery, K.O., 1961. A simple method of measuring beach profiles. Limnol. Oceanogr. 6, 90–93.
Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., 2014. Plastic pollution in the world's oceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS One 9, e111913.
Eriksson, C., Burton, H., Fitch, S., Schulz, M., Van den Hoff, J., 2013. Daily accumulation rates of marine debris on sub-Antarctic island beaches. Mar. Pollut. Bull. 66, 199–208.
Garcon, J.S., Grech, A., Moloney, J., Hamann, M., 2009. Relative exposure index: an important factor in sea turtle nesting distribution. Aquat. Conserv. 20, 140–149.
Gregory, M.R., 2009. Environmental implications of plastic debris in marine settings — entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philos. Trans. R. Soc. Lond. B 364, 2013–2025.
Henderson, J.R., 2001. A pre- and post-MARPOL Annex V summary of Hawaiian monk seal entanglements and marine debris accumulation in the Northwestern Hawaiian Islands, 1982–1998. Mar. Pollut. Bull. 42, 584–589.
Howell, E.A., Bograd, S.J., Morishige, C., Seki, M.P., Polovina, J.J., 2012. On North Pacific circulation and associated marine debris concentration. Mar. Pollut. Bull. 65, 16–22.
Kubota, M., 1994. A mechanism for the accumulation of floating marine debris north of Hawaii. J. Phys. Oceanogr. 24, 1059–1064.
Law, K.L., Morét-Ferguson, S.E., Goodwin, D.S., Zettler, E.R., DeForce, E., Kukulka, T., Proskurowski, G., 2014. Distribution of surface plastic debris in the Eastern Pacific Ocean from an 11-year data set. Environ. Sci. Technol. 48, 4732–4738.
Leite, A.A., Santos, L.L., Costa, Y., Hatja, V., 2014. Influence of proximity to an urban center in the pattern of contamination by marine debris. Mar. Pollut. Bull. 81, 242–247.
McCullagh, P., Nelder, J.A., 1989. Generalized Linear Models vol. 2. Chapman and Hall, London (532 pp.).
McDermid, K.J., McMullen, T.L., 2004. Quantitative analysis of small-plastic debris on beaches in the Hawaiian archipelago. Mar. Pollut. Bull. 48, 790–794.
McLachlan, A., Dorvlo, A., 2005. Global patterns in sandy beach macrobenthic communities. J. Coast. Res. 21, 674–687.
Moore, C., Moore, S., Leecaster, M., Weisberg, S., 2001. A comparison of plastic and plankton in the North Pacific central gyre. Mar. Pollut. Bull. 42, 1297–1300.
Morishige, C., Donohue, M.J., Flint, E., Swenson, C., Woolaway, C., 2007. Factors affecting marine debris deposition at French Frigate Shoals, Northwestern Hawaiian Island Marine National Monument, 1990-2006. Mar. Pollut. Bull. 54, 1162–1169.
Narasimhan, R., 2014. weatherData: get weather data from the web. R package version 0.4.1. http://CRAN.R-project.org/package=weatherData.
National Climate Data Center (NCDC), 2015. NOAA Automated Weather Observing System (AWOS) Stations. National Climatic Data Center, Ashville, North Carolina, USA (Data Accessed February 2015. http://www.ncdc.noaa.gov/).
Ocean Conservancy, 2014. Turning the tide on trash 2014 report. Retrieved from http://www.oceanconservancy.org/our-work/marine-debris/icc-data-2014.pdf.
Opfer, S., Arthur, C., Lippiatt, S., 2012. NOAA Marine Debris Shoreline Survey Field Guide. U.S. National Oceanic and Atmospheric Administration Marine Debris Program.
Pacific Whale Foundation, n.d. Fishieng line recycling in Hawai'i. Retrieved from http://www.pacificwhale.org/content/fishing-line-recycling-hawaii
Pichel, W.G., Churnside, J.H., Veenstra, T.S., Foley, D.G., Friedman, K.S., Brainard, R.E., Nicoll, J.B., Zheng, Q., Clemente-Colón, P., 2007. Marine debris collects within the North Pacific Subtropical Convergence Zone. Mar. Pollut. Bull. 54, 1207–1211.
Puotinen, M.L., 2005. An automated GIS method for modeling relative wave exposure within complex reef-islands systems: a case study of the Great Barrier Reef. In: Zerger, A., Argent, R. (Eds.), Congress of the Modelling and Simulation Society of Australia and New Zealand, 1497–1443.
Ribic, C.A., Sheavly, S.B., Rugg, D.J., Erdmann, E.S., 2012a. Trends in marine debris along the U.S. Pacific Coast and Hawai'i 1998–2007. Mar. Pollut. Bull. 64, 994–1004.
Ribic, C.A., Sheavly, S.B., Klavitter, J., 2012b. Baseline for beached marine debris on Sand Island, Midway Atoll. Mar. Pollut. Bull. 64, 1726–1729.
Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. Philos. Trans. R. Soc. B 364, 1999–2012.
Sakamoto, Y., Ishiguro, M., Kitagawa, G., 1986. Akaike Information Criterion Statistics. D. Reidel, Dordrecht, The Netherlands.
Sanderson, M., 1993. Prevailing Trade Winds: Climate and Weather in Hawaii. University of Hawaii Press, Honolulu (156 pp.).
Secretariat of the Convention on Biological Diversity (SCBD) and the Scientific and Technical Advisory Panel—GEF, 2012D. Impacts of Marine Debris on Biodiversity: Current Status and Potential Solutions. Technical Series No. 67, p. 61.
Sheavly, S.B., Register, K.M., 2007. Marine debris & plastics: environmental concerns, sources, impacts and solutions. J. Polym. Environ. 15, 301–305.
Short, A.D., 1996. The role of wave height, slope, tide range and embaymentisation in beach classification: a review. Rev. Chil. Hist. Nat. 69, 589–604.
Slip, D.J., Burton, H.R., 1991. Accumulation of fishing debris, plastic litter, and other artefacts, on Heard and Macquarie Islands in the Southern Ocean. Environ. Conserv. 18, 249–254.
Smith, D.A., Markic, A., 2013. Estimates of marine debris accumulation on beaches are strongly affected by the temporal scale of sampling. PLoS One 8, e83694.
U.S. Army Coastal Engineering Research Center (USACERS), 1977. third ed. Shore Protection Manual vol. 1. US Government Printing Office, Washington.
United States Environmental Protection Agency (U.S. EPA), 2011. Marine debris in the North Pacific: a summary of existing information and identification of data gaps. Retrieved from http://www.epa.gov/region9/marine-debris/pdf/MarineDebris-NPacFinalAprvd.pdf.
Walker, T.R., Grant, J., Archambault, M.-C., 2006. Accumulation of marine debris on an intertidal beach in urban park (Halifax Harbour, Nova Scotia). Water Qual. Res. J. Can. 41, 256–262.
Wood, S.N., 2011. Fast stable restricted maximum likelihood and marginal likelihood estimation of semiparametric generalized linear models. J. R. Stat. Soc. Ser. B Stat Methodol. 73, 3–36.