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Tracking the sources and sinks of local marine debris in Hawai'i

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ABSTRACT

Plastic pollution has biological, chemical, and physical effects on marine environments and economic effects on coastal communities. These effects are acute on southeastern Hawai'i Island, where volunteers remove 16 metric tons of debris annually from a 15 km coastline. Although the majority is foreign-origin, a portion is locally-generated. We used floating debris-retention booms in two urban waterways to measure the input of debris from Hilo, the island's largest community, and released wooden drifters in nearby coastal waters to track the fate of that debris. In 205 days, 30 kilograms of debris (73.6% plastic) were retained from two watersheds comprising 10.2% of Hilo's developed land area. Of 851 wooden drifters released offshore of Hilo in four events, 23.3% were recovered locally, 1.4% at distant locations, and 6.5% on other islands. Comparisons with modeled surface currents and wind were mixed, indicating the importance of nearshore and tidal dynamics not included in the model. This study demonstrated that local pollutants can be retained nearby, contribute to the island's debris-accumulation area, and quickly contaminate other islands.

1. Introduction

Plastic pollution in the marine environment impacts human communities directly through reduced tourism income, increased cost of cleanup, threats to navigation and safety, contamination of food sources, loss of aesthetic value, and other public health hazards (reviewed in Thompson et al. 2009). It impacts those same communities indirectly by threatening marine organisms and habitats though entanglement and ingestion by invertebrates, fishes, birds, turtles, and marine mammals, smothering of the benthos, leaching of plasticizers, concentration of persistent organic pollutants in seawater, changing the physical properties of sediment, and the transport of organisms via rafting (reviewed in Cole et al. 2011, Gregory 2009).

These effects are particularly acute in the Hawaiian Archipelago, in part because of its location proximal to the major debris accumulation zone of the North Pacific Gyre (Howell et al. 2012). In the northwestern portion of the island chain, the sensitive habitats of the Papahānaumokuākea Marine National Monument are threatened by marine debris, especially derelict fishing gear (Donohue et al. 2001). Marine debris also affects the marine environment and human communities on the southeastern inhabited islands. Residents are tied to the ocean, not only through a dependence on tourism and shipping, but also via aquatic activities (such as fishing, surfing, and canoeing) that are integral to their lifestyle and culture. Near the southern end of the archipelago's largest island, Hawai'i, lies Kamilo Point, an area famous for debris accumulation (Fig. 1). Since 2003, the Hawai'i Wildlife Fund (www.wildhawaii.org) has removed an average of 16 metric tons of debris per year from this 15 kilometer coastline.

The plastic debris at Kamilo consists of derelict fishing gear, miscellaneous large items, and a high, but patchily distributed, concentration of polyethylene and polypropylene fragments (Carson et al. 2011). The majority of identifiable items appear to be of non-Hawai'i origin, as evidenced by heavily degraded or fouled surfaces, foreign-language labels, markings, and logos on items not labeled for sale in the United States, or aquaculture and fishing industry equipment not in use on the islands (e.g. Ebbesmeyer et al. 2012). However, some items do appear to be of local origin, as evidenced by fresh, unfouled surfaces, and commonly used brand names. The local-origin debris is unlikely to have been littered directly on the coastline because the area is difficult to access and

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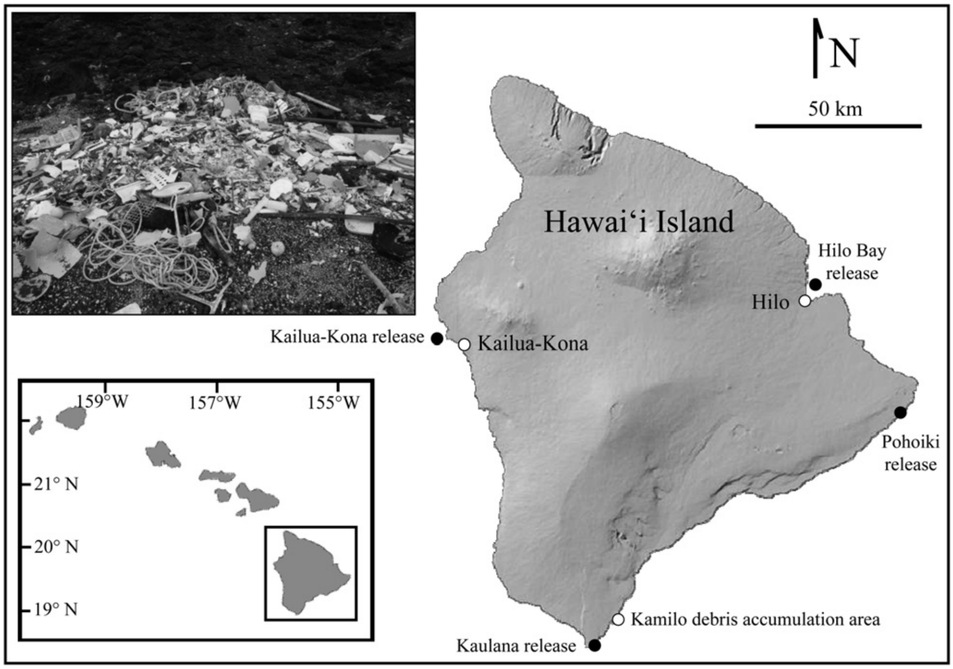

Fig 1. Map of the study areas around Hawai'i Island, and inset picture of typical debris accumulation on Kamilo Point.

not a tourist destination. Therefore, the same hydrodynamic forces which deposit large amounts of foreign debris on this coastline may also carry local debris. We hypothesize that prevailing northeasterly trade winds, and their associated surface currents (Jia et al. 2012), make the east coast of Hawai'i Island the most likely source of local debris to the Kamilo area.

Although plastic pollution from distant locations in the Pacific poses a great threat to Hawai'i (Brainard et al. 2001, Donohue 2005, Ebbesmeyer et al. 2012), this pollution is also more difficult to prevent with local action than Hawai'i-sourced debris. In this study, we test whether or not waste from the island's large population centers washes up on the island's main debris accumulation areas. Specifically, we investigate the following two questions:

1) What is the amount, composition, and timing of debris reaching the ocean from the island's largest population center, as measured by floating debris retention booms in two urban waterways?
2) What are the pathways of Hilo debris and debris from other island areas once it reaches the ocean, as traced by drifters and simulated by ocean models?

2. Design of experiments

2.1. Debris-retention Booms

One floating debris-retention boom was placed in each of two waterways in Hilo (Fig. 2), the largest population center on the island of Hawai'i (43,263 people as of the 2010 census). The first (#1 in Fig. 2) was placed in the Wailoa River watershed, which drains the predominantly residential southern portion of the city. The watershed area is 255.4 km^2 extending to the top of the massive Mauna Loa volcano; however, due to the highly porous nature of the basaltic rock, surface runoff only becomes a relevant factor in the movement of debris in the lower, developed 10.0 km^2 of the watershed (Parham et al. 2008). The boom spanned a 25-meter-wide concrete flood-control channel at the mouth of the river as it flows into Waiākea Pond. The pond is a brackish-water, tidally-influenced water body that opens to Hilo Bay 1.5 km north of the boom.

The second boom (#2 in Fig. 2) was placed in the 'Alenaio Stream watershed, which drains a smaller portion of urban Hilo, including the southern end of the downtown commercial district. The watershed area extends 187.3 km^2 up the slopes of the Mauna Loa volcano; however, only the developed lower 4.3 km^2 (Parham et al. 2008) is likely to produce significant synthetic debris runoff. The boom crossed a six-meter-wide stone flood-control channel as the stream empties into Waiākea Pond. The bay entrance is located 1.2 km east of the boom.

The booms collected debris from only 10.2% of Hilo's developed land area, representing approximately 4,400 people. Northern portions of the city are drained by the Wailuku River, a large watershed (653.2 km^2) of forested land that experiences extreme flows during frequent storm events which would be likely to destroy attempted boom placements with the force of water and drifting logs. The majority of runoff from the downtown commercial district reaches the bay via a decentralized network of underground storm drains which are difficult to sample effectively. To the south of the study area, the Keaukaha area is also drained via groundwater and decentralized channels that would be impossible to sample effectively for debris. These logistical considerations prevented more of Hilo's drainage area from being studied. The boom placements at the point where the two study watersheds empty into Waiākea Pond are advantageous because standing water supports the booms during low flow while dissipating some of the energy from high flow events.

The booms were anchored to either side of the two drainage channels, and remained in place for 205 days from September 2011 to April 2012. They consisted of flotation chambers extending about 0.3 m above the water surface (Fig. 2), and a solid, impermeable curtain weighted with chain extending about 0.3 m below the water surface. Debris was removed twice a week during the study period, with additional checks after storm events. To collect the debris, the booms were detached from one shoreline and pulled across to encircle the debris close to the other shoreline where it

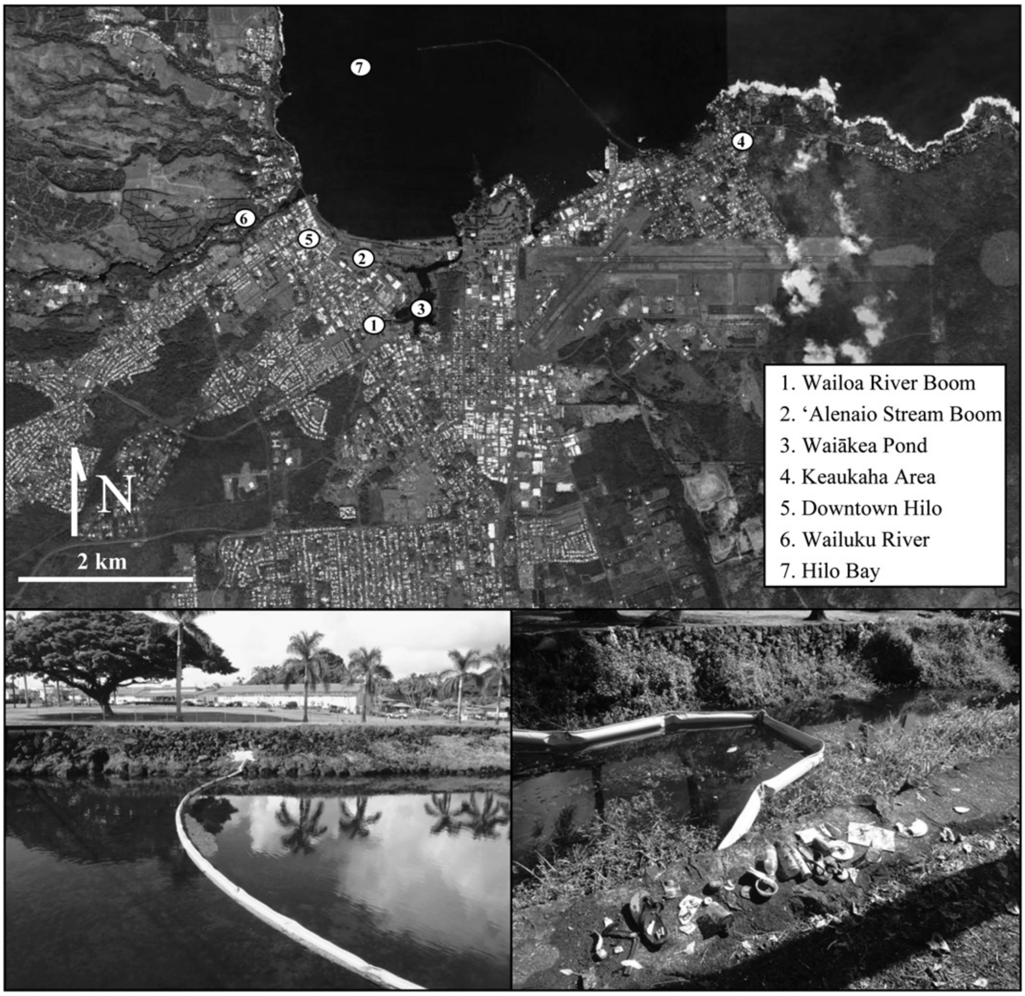

Fig 2. Satellite photo of the study area in Hilo, Hawai‘i Island, and pictures of the Wailoa River Boom (left) and ‘Alenaio Stream Boom (right) with typical debris shown in the foreground.

could be easily removed with a dip net. In the laboratory, captured items were separated from organic debris, rinsed, and then dried for weighing and classification into one of ten categories (Table 1). We have no quantitative data on the efficiency of debris capture by the booms. Visual observations showed that the booms were most efficient at capturing high-buoyancy items such as plastic bottles, and could not always retain low-buoyancy items such as plastic bags, especially during high flow conditions.

We used linear regression to test for a relationship between the timing of plastic captures and local precipitation, as measured by National Weather Service rainfall gauges. Cumulative rainfall that occurred between debris samplings was compared to the total weight of debris found in the booms during the corresponding sampling period.

2.2. *Drifter Experiments*

Degradable wooden drifters were constructed to approximate the movement of Hawai‘i-sourced debris. The drifters were made of pine blocks approximately 7.6 cm long, 8.9 cm wide, and 3.8 cm high, branded with a message including release location code, contact phone number, and email address. In seawater, the blocks initially floated with approximately 1 cm of windage, which was reduced to almost zero after several hours of water absorption. A test block placed in a bucket of seawater remained positively buoyant for approximately 80 days before sinking.

We released 851 blocks at the same Hilo Bay location (19° 45’ 06” N, 155° 03’ 51” W) in two deployments, one in October 2011 and another in March 2012. To assess the effect of hypothetical along-

Table 1
Dry weight of debris captured by two floating retention booms in Hilo, HI, USA over 205 days. Numerals in parenthesis below the weights are the number of items of that category. “Misc.” = miscellaneous items that do not belong in the other categories, including plastic items and items made of multiple materials; PET = polyethylene terephthalate; PE = polyethylene.

boom	plastic items (kg)							aluminum (kg)	glass (kg)	misc. (kg)	total (kg)
	PET bottles	cigarettes	PE packaging	bags	cups / lids	footwear	styrofoam				
Wailoa River	1.79 (69)	0.34 (1004)	0.80	0.43 (50)	0.50 (15)	0.15 (1)	0.76	0.13	0.01	5.60	10.52
‘Alenaio Stream	3.30 (121)	0.07 (263)	1.05	1.83 (121)	1.05 (53)	2.04 (8)	0.63	1.08	2.08	6.29	19.43
Total	5.09 (190)	0.41 (1267)	1.85	2.26 (171)	1.55 (68)	2.19 (9)	1.39	1.21	2.09	11.89	29.95

shore jets, induced by tides, each event was split into two tide-state releases: at slack-before-flood (low tide) and at slack-before-ebb (high tide). Prevailing westward flow around Hawaiian Islands (Jia et al. 2012) reduces the probability of debris transport from the west coast of Hawai'i Island to the Kamilo accumulation area. To verify this hypothesis, we also released drifters near the island's second-largest population center at Kailua-Kona. We placed 230 drifters offshore of Kailua-Kona (19° 40' 2" N, 156° 2' 15" W) in two tide-state releases in October 2011. Two additional release locations not near population centers were used to help describe the movement of debris around the island. We deployed 236 drifters offshore of Pohoiki, near the eastern tip of the island, and 230 blocks offshore of Kaulana, near the southern tip of the island (Fig. 1), each in two tide-state releases in October 2011. All releases were made from watercraft approximately 1 km offshore, because we were not interested in studying surf zone debris-movement processes.

The telephone hotline and email account were monitored continuously after releases to receive reports of recoveries. Members of the public that located blocks were asked to report the time, date, and location of the recovery event, as well as block release code and whether or not they removed the block from the shore (to prevent duplicate reports). First reports from certain areas were used to calculate maximum drift speeds from release to destination, and subsequent recoveries were assumed to have been beached nearby and not recovered immediately.

2.3. Ocean Model of Surface Currents

The SCUD (Surface CUrrents from Diagnostics) model was developed at the International Pacific Research Center (IPRC) to assess surface velocities using global, near-real time satellite data of altimetric sea level anomaly and scaterometric vector wind (Maximenko and Hafner 2010). Sea level anomaly, referenced to the mean dynamic topography found in Maximenko et al. (2009), was used to compute absolute geostrophic velocity and wind to assess Ekman currents. Geographically-varying coefficients of the model were tuned using trajectories of almost 15,000 satellite-tracked drifting buoys of the Surface Velocity Program and Global Drifter Program (http://www.aoml.noaa.gov/phod/dac/index.php). Model velocities are calculated daily, on a 1/4° global grid. The accuracy of the model deteriorates near shore due to higher errors in satellite data and increased complexity of dynamics. It is challenging to use the SCUD model to assess the movement of a wooden block, whose design is very different from the drifters employed by the Global Drifter Program. However, SCUD currents were found informative to trace such differently shaped instruments as the whale-tracking gear, operated by the US National Oceanic and Atmospheric Administration's (NOAA) Hawaiian Islands Humpback Whale Sanctuary, and the experimental profiling float (during its visits to the ocean surface) of the US National Aeronautics and Space Administration's (NASA) Jet Propulsion Laboratory. Specific to marine debris, the solution of the statistical version of the model corresponds satisfactorily to the distribution of plastic fragments in open waters (Maximenko et al. 2012). Additionally, SCUD was found helpful in simulating the motion of heterogeneous tsunami debris from Japan, including its circulation in the North Pacific and landing on shorelines of different countries (Maximenko and Hafner, unpublished data[1]). Despite the limited applicability of the SCUD model to the motion of wooden blocks in the nearshore area, the overall simplistic formulation of the drifter exchange between different islands, and limited instrumental power, make reasonable the use of the readily-available SCUD model as a framework for the project.

The virtual release point for simulations was moved 24 km offshore of the drifter release point to conform to the model space of SCUD. 10,000 virtual drifters were randomly placed within the 1/4° squared grid cell offshore of Hilo Bay on the October and March drifter release dates. Their trajectories were computed for 14 days to encompass the approximate period of first recoveries for the wooden drifters. Duplicate simulations were run for each release including a 2% windage factor to compare with the previous simulations.

3. Results and Discussion

3.1. Debris-retention Booms

In 205 days, the two booms captured 29.9 kg of anthropogenic debris, 73.6% of which was plastic by weight (Table 1). The largest defined category was polyethylene terephthalate (PET, "#1") bottles, which comprised 17% of the total by weight. They were followed by disposable plastic bags (7.5%), footwear (7.3%), glass (7.0%), and polyethylene (PE) packaging (6.2%). A large portion of the total debris was miscellaneous items, including sports equipment, fishing gear, toiletries, household items, and fabrics. The most numerous category was cigarette butts (1267 items), although they only made up 1.4% of the debris by weight. Over a third (35.6%) of the material included plastic, aluminum, and glass packaging for which recycling facilities are readily available.

The accumulation of debris at the booms was significantly related ($p < 0.001$) to precipitation events in a linear regression (Fig. 3), although rainfall did not explain the variation in debris weight collected to the extent that might be expected given that surface runoff is the most likely transport mechanism to waterways. Only 37% of the variation in total debris weight collected could be explained by variation in rainfall. However, if littering rates are more or less constant in time (Seco Pon and Becherucci 2012), the first precipitation event after a dry period is likely to carry a disproportionate amount of debris compared to subsequent rainfall events, regardless of their magnitude, that occur before new litter can accumulate (Moore et al. 2011).

The amount of debris collected at each boom did not correspond to the land area drained by the waterway. The Wailoa River drains over twice the developed land area as 'Alenaio Stream, but collected half the debris (Table 1). Differing land-use within the urban area is the most likely explanation (Seco Pon and Becherucci 2012), with

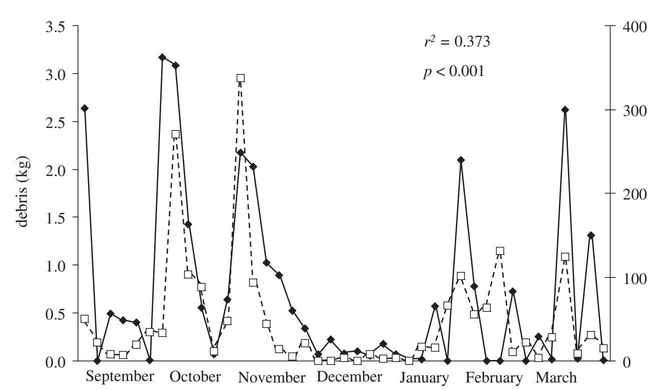

Fig 3. Total anthropogenic debris (filled diamonds, solid lines) at debris retention booms in two watersheds and accumulated rainfall (open squares, dashed lines) in between monitoring events at the booms. The r^2 and p-values are from a linear regression between accumulated debris and rainfall at each sampling.

[1] Model results available at: http://iprc.soest.hawaii.edu/news/marine_and_tsunami_debris/IPRC_tsunami_debris_models.php1.

higher littering rates possible in the downtown commercial district, partially drained by the ʻAlenaio Stream, compared to residential districts. Because of the potential variation in litter by specific land-use, it is difficult to calculate the total input of debris from an urban area on the basis of two retention booms. However, under the reasonable assumption that littering rates do not vary significantly with season (Seco Pon and Becherucci 2012), the booms captured debris at a rate of 53.3 kg per year. Extrapolating that collection rate from 10.2% of the city's land area to the entire city yields more than 500 kg of marine debris produced each year for a city of over 43,000 people. This estimate does not include litter that is blown into the ocean by wind, or litter directly deposited into the marine environment on beaches or from boats.

There are many reasons why that rough calculation may be a significant underestimate of debris produced, and chief among them is the inefficiency of capture by the booms. During high flow events that are common in Hilo, we observed low-buoyancy items such as plastic bags slide underneath the booms and avoid capture. Estimates of the amount of high-buoyancy items such as capped PET bottles are probably more accurate, as they seemed to be retained on the surface even during high-flow conditions. Floating retention booms with subsurface netting anchored to the bottom would perform better at both quantifying debris and preventing its entry into the ocean. Such devices were not possible at these locations due to risk of sea turtle entanglement and other threats to wildlife.

Several studies have attempted to quantify marine debris inputs from stormwater runoff using a variety of capture devices, but few are published in the primary literature (reviewed in Ryan et al. 2009). Our impermeable curtains across entire drainage channels were better suited to prevent buoyant debris from entering the ocean in moderate flows than they were to quantify all debris inputs accurately under a variety of conditions. Sampling a portion of the stream with fine-mesh netting, as did Moore et al. (2011) in Los Angeles, would provide more accurate estimates of input rates, especially for micro-debris in high flow regimes.

3.2. *Drifter Experiments*

Of the 1547 wood-block drifters released at four locations around the island, 387 (25%) were reported recovered. Of those recovered, 302 (78%) were found within 25 km of the release point. The remaining 85 (22%) were found at distant locations on Hawaiʻi Island or on one of three other Hawaiian islands (Table 2, Fig. 4). The two October 2011 releases from Hilo Bay had markedly different outcomes. No recoveries were made from the low-tide release, whereas 24.3% of the blocks released at high-tide were recovered on the islands of Maui (42 blocks), Lanaʻi (8 blocks), and uninhabited Kahoʻolawe (5 blocks). The Maui recoveries, in particular, were spread over the entire island, although a majority were encountered in the Makena (22 blocks) and Kahikinui (10 blocks) portions of the southern coastline. The first recovery, at Hana on the eastern tip of Maui, occurred eight days after release. This corresponds to a 23 cm s^{-1} mean drift speed. The first recovery on the north coast of Lanaʻi occurred 10 days after release (30 cm s^{-1} drift speed).

The two March 2012 releases from Hilo Bay had similar outcomes, although they did not match the results of the earlier releases. A large proportion of both the low-tide (51.5%) and high-tide (46.8%) releases were retained within the bay, recovered on the bay's southern Keaukaha coastline (Fig. 2) as soon as two days after release. Only thirteen blocks from the high-tide release were recovered outside the bay. One block drifted north to the northernmost tip of the island, and the other twelve drifted south, reaching as far as Kamilo Point near South Point (Fig. 4).

Releases from the island's other major population center, Kailua-Kona, had no reported recoveries. Both releases from Pohoiki on the eastern tip of the island were recovered locally (within 10 km) in large numbers, 49.6% and 37.4% for the low- and high-tide events, respectively (Table 2). Thirteen blocks from the high-tide release traveled southwest and were found at the major debris-accumulation area at Kamilo Point (Fig. 4). Only four drifters were reported from the Kaulana releases at the southern tip of the island. Two each from the high- and low-tide releases were encountered on the island of Lanaʻi. In contrast to other drift block recoveries on Lanaʻi, these were all found 61 or more days after release. These blocks, drifting at a considerably slower speed (5 cm/s) than other Lanaʻi recoveries, could have taken an offshore path through the field of eddies which often form in the lee of Hawaiʻi Island (Jia et al. 2012).

The drifter results show that buoyant pollution from Hawaiʻi Island's largest population center can take a variety of paths. Tidal cycles or other variations that occur on the timescale of hours can cause strong dispersion of blocks released together, or result in completely different trajectories. Hilo Bay drift blocks traveled northwest, quickly beaching on three other islands, and they were also retained locally, washing up at local beach parks after a short residence in the bay. Although only one drifter out of over 800 released was recovered at Kamilo, this block establishes the drift path for Hilo debris to beach at the island's debris-accumulation area. The same path was also demonstrated in two steps - Hilo Bay blocks found at Pohoiki near the eastern tip of the island, and blocks released at Pohoiki found at Kamilo (Fig. 4). Ongoing experiments carried out while this manuscript was in review support the Hilo to Kamilo pathway. Six of 200 blocks released from Hilo Bay in late October 2012 have been recovered at Kamilo or

Table 2
Wood-block drifter releases and reported recoveries in the Hawaiian Islands.

release				recovery					
location	tide	number	date	total	Hawaiʻi Island		Maui	Lanaʻi	Kahoʻolawe
					local	distant			
Hilo Bay 1	low	220	10/24/11	0.0%					
	high	226		24.3%			18.6%	3.5%	2.2%
Hilo Bay 2	low	200	03/23/12	51.5%	51.5%				
	high	205		53.2%	46.8%	6.3%			
Pohoiki (East Point)	low	121	10/24/11	60.3%	49.6%	10.7%			
	high	115		37.4%	37.4%				
Kaulana (South Point)	low	115	10/27/11	1.7%				1.7%	
	high	115		1.7%				1.7%	
Kailua-Kona	low	115	10/26/11	0.0%					
	high	115		0.0%					
total		1547		25.0%	19.5%	1.7%	2.7%	0.8%	0.3%

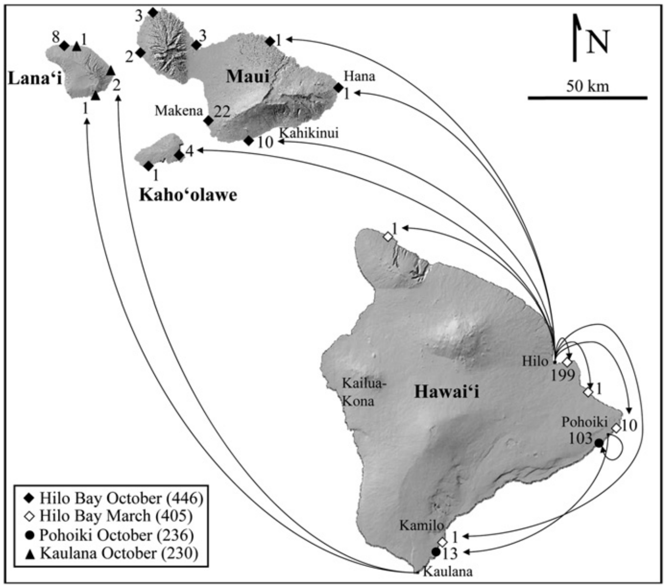

Fig 4. Locations of all reported drifter recoveries. Multiple recoveries in one area are represented by one symbol, with the adjacent numeral denoting the number of recoveries in that area. Numbers in parenthesis in the figure legend are the total number of blocks released at that event. Arrows connect release and recovery locations, and do not represent drift paths. Not all of the release-recovery connections are shown for clarity.

along this coastline at press time, with no recoveries elsewhere. The eastern half of the island, including Hilo, remains the most probable source of the local debris that arrives at Kamilo.

No drift blocks were recovered from the Kailua-Kona releases, and only four were recovered from Kaulana releases. The paucity of recoveries for blocks released on the leeward (i.e. westward) side of the island is not surprising. The same prevailing currents that sweep debris from east Hawaiʻi westward would send west Hawaiʻi debris toward open water and keep leeward beaches relatively clean. This finding matches the observation of larval dispersal by direct detection of parent-offspring pairs in reef fish on Hawaiʻi Island (Christie et al. 2010). Parents located on the eastern and southern coasts of the island seeded recruits to the western coast, but the reverse was not detected.

The 75% of blocks not reported recovered could have traveled to a variety of destinations. SCUD model results (see below and Fig. 5) show many could have been advected away from the islands into the open ocean. These drifters will likely degrade or sink within months. Others may have landed on seldom-visited parts of the state such as much of the coastline of Kahoʻolawe Island. Others could be lodged or buried in sediment, rocks, or crevices and difficult to see. Still others may have been found and not reported, as suggested by some who called many weeks after recovery because they forgot about the block for some time. Many blocks may have beached one or more times, been refloated, and beached in secondary locations, as evidenced by some blocks that appeared more abraded (in pictures sent by recoverers) than others. Although difficult to quantify, beaching and refloating is a common

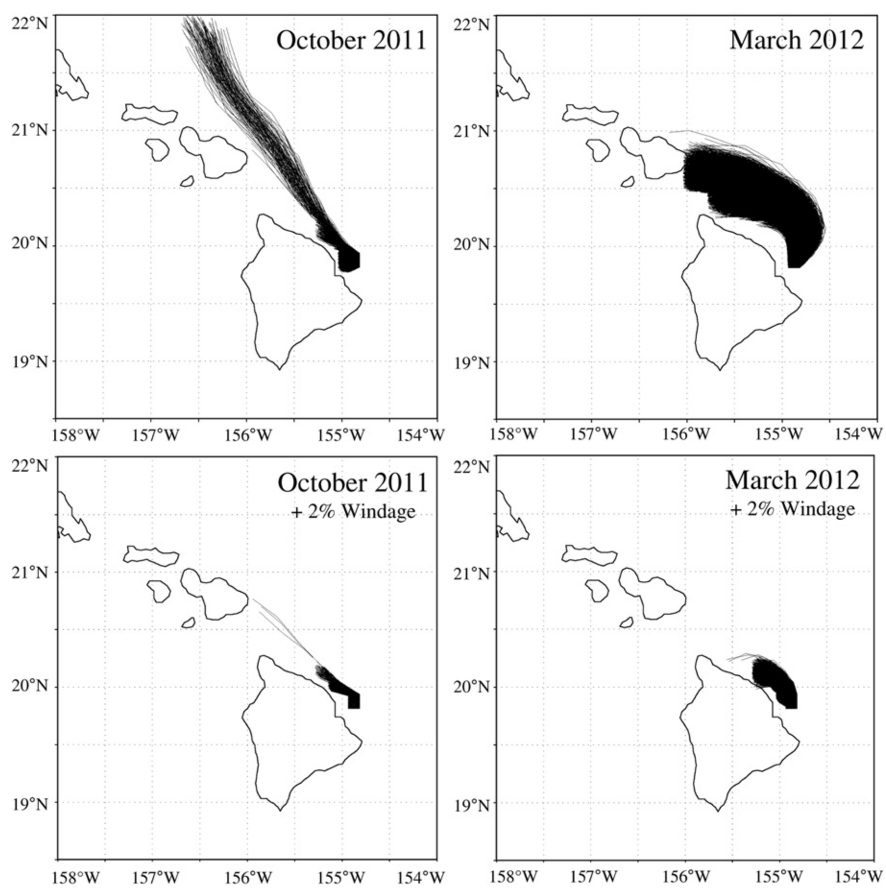

Fig 5. Results of SCUD model particle releases corresponding to the drifter releases in Hilo Bay. Particle trajectories represent drift pathways during the first two weeks after release. The virtual release point was moved 24 km offshore of the drifter release points to allow for model function. Top panels show model runs without any windage factor included. The bottom panels depict identical model runs with the addition of a 2% windage factor.

behavior of the plastic debris the blocks are meant to represent (Garrity and Levings 1993).

How representative our drifter results are to the drift of marine debris depends on how well their trajectories reproduce the motion of plastic pollution. Matching the ratio of surface area exposed to the wind to the submerged drag area is the key criterion for similarity (Wiese and Jones 2001). The complication with plastic litter, of course, is the diversity of shapes and buoyancies represented. We designed our drifters with minimal windage, similar to a large amount of the debris captured by our booms (Table 1) such as bags, fragments, and packaging. However, more buoyant items with more windage such as capped PET bottles are likely not well represented by the drift blocks. Heterogeneity of debris found on some beaches and missing from others indicates significant robustness of pathways of different objects on a local scale and justifies the design of our drifter experiment.

3.3. Comparison with Ocean Model

The results of SCUD model simulation for Hilo Bay releases (Fig. 5) corresponded generally to the observed drifter recoveries in some cases. In October 2011, both the modeled particles and the drifters were quickly transported northward. In the model, however, they were swept past Maui toward the subtropical gyre accumulation zone and did not make landfall. It is possible that many blocks from both tide-state releases traveled the modeled path, especially from the low-tide release for which no blocks were recovered. Model-predicted current speeds of 20 - 30 cm/s corresponded well to the timing of first recoveries on the islands of Maui and Lanaʻi. Including an estimate of the direct impact of the wind changed the modeled results considerably, as the onshore winds pushed most of the particles onto the shoreline north of Hilo (Fig. 5) where no blocks were recovered. The actual block recoveries in Maui represent a middle ground between the two scenarios, suggesting that both wind and surface currents affected the blocks' drift. A small number of particles in SCUD traveled toward actual block recovery locations on Maui (Fig. 5).

Ironically, the surface current model did predict a large amount of Maui recoveries for the March 2012 release (Fig. 5), when there were none. One block, recovered on the northern tip of Hawaiʻi Island, conformed to the model prediction. The other 211 recoveries, however, were local or southward. A major possible reason for the discrepancy between model predictions and drifter observations was the need to move the virtual release point offshore of the actual release point. The SCUD model does not include nearshore processes, the same processes which necessarily transport land-sourced debris for at least a portion of their journey. In the case of the March release, many blocks retained in the bay probably did not ever enter the model space of SCUD. In October, the blocks were apparently quickly moved offshore and into the modeled current area. Adding the effect of windage to the SCUD model for the March release (Fig. 5) shows increased transport of the particles onshore, closer to realized drift of the blocks.

The differences between the modeled particles and the drift blocks can be partially attributed to the uncertain effects of windage, especially before the blocks waterlogged and floated lower in the water. This uncertainty increases when the shape or buoyancy of the floating object is unknown, as is often the case for the variety of objects that constitute marine debris. Other discrepancies may result because the SCUD model is a daily product and does not account for differences in mixed, semi-diurnal tidal state, which probably affected the drifter results considerably.

Most ocean models used to predict the spread of marine debris operate on a larger-scale than the questions presented here (reviewed in Potemra 2012). The development of ocean models that accurately describe the nearshore environment around Hawaiʻi would aid in the study of the transport of marine debris around the islands. Particles which enter the nearshore environment in the SCUD model are considered beached (Fig. 5), despite the fact that they are kilometers from shore in reality and would likely continue their drift. Drifter experiments are useful tools, but cannot be deployed continuously to describe hourly or daily fluctuations in surface currents throughout the year as models can. With more nearshore data from high-frequency radar or current meters, models validated with episodic drifter experiments could better describe the factors that control the local sources and sinks of marine debris.

4. Implications

These results demonstrate the increased importance of East Hawaiʻi's waste management practices to the rest of the state. In the prevailing currents, Hilo lies "upstream" of the state's other communities and habitats, and material entering the ocean there can begin to pollute other islands quickly. Our October release of drift blocks shows that pollutants entering the ocean at Hilo can reach widespread locations around the islands of Maui County in as little as eight days. Hilo is the only deepwater port for the island of Hawaiʻi, and as such receives a large amount of shipping, cruise liner, and oil barge traffic. Of course, the results of this study cannot be automatically extrapolated to all kinds of pollution. For example, oil spilled originally at the sea surface is known to gradually evaporate, dissolve, change chemically, and, finally, sink. Based on our observations, any pollutant surviving on the ocean surface for a period of weeks has a good chance to spread among the Hawaiian Islands.

The steady stream of plastic debris from Hilo and many communities is an ongoing spill of solid-phase petroleum that occurs with each rain storm. This spill is quite preventable. There are no fees for domestic waste disposal at island transfer stations. Several private and public recycling facilities in Hilo accept or purchase materials that made up a third of the debris collected in the booms. Much of the waste collected was single-use containers or bags, most likely used for a short period of time (minutes or hours) before being discarded. If such containers were designed for multiple reuses, both the volume of waste and the impacts to habitats and communities could be reduced. All four counties of the State of Hawaiʻi, for instance, have each recently passed legislation to limit the use of disposable plastic shopping bags (Bly 2012).

Although waste that travels from local sources to local sinks is the easiest to track and potentially mitigate, it is often a small portion of both pollution produced and pollution received by a given area. Even if all of the minimum 0.5 metric tons of marine debris from Hilo traveled to Kamilo Point each year, it would only make up 3% of the total debris removed from that coastline annually. Similarly, plastic waste from Hilo, other parts of the island, or the rest of the state still persists in the ocean even if it is not beached on one of the inhabited or uninhabited islands of the Hawaiian Archipelago. Local waste-management and consumer choices that reduce the amount of plastic entering the ocean will certainly reduce local impacts, but of equal importance is reducing each community's contribution to the global marine debris problem.

Disclosures

The sponsors, Will J. Reid Foundation, had no involvement in study design, collection or interpretation of data, or manuscript preparation. The authors declare no conflicts of interest. H. Carson designed the study, supervised data collection of both booms and

drifters, performed statistical analysis, and drafted the manuscript. M. Lamson helped design the study, assisted with drifter deployment and data collection, and edited the manuscript. D. Nakashima and D. Toloumu helped design the study, collected the boom data, assisted with drifter construction and deployment, and edited the manuscript. J. Hafner and N. Maximenko helped design the study, carried out ocean modeling, and edited the manuscript. K. McDermid helped design the study, provided lab space and technical advice, mentored students, and edited the manuscript. All authors have approved the manuscript as submitted.

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