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Mapping coastal marine debris using aerial imagery and spatial analysis☆

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ABSTRACT

This study is the first to systematically quantify, categorize, and map marine macro-debris across the main Hawaiian Islands (MHI), including remote areas (e.g., Niihau, Kahoolawe, and northern Molokai). Aerial surveys were conducted over each island to collect high resolution photos, which were processed into orthorectified imagery and visually analyzed in GIS. The technique provided precise measurements of the quantity, location, type, and size of macro-debris ($> 0.05\ m^2$), identifying 20,658 total debris items. Northeastern (windward) shorelines had the highest density of debris. Plastics, including nets, lines, buoys, floats, and foam, comprised 83% of the total count. In addition, the study located six vessels from the 2011 Tōhoku tsunami. These results created a baseline of the location, distribution, and composition of marine macro-debris across the MHI. Resource managers and communities may target high priority areas, particularly along remote coastlines where macro-debris counts were largely undocumented.

1. Introduction

Marine debris presents physical, biological, and chemical threats to coastal ecosystems (Coe and Rogers, 1997; Derraik, 2002; Sheavly and Register, 2007; EPA, 2011; Gall and Thompson, 2015). It can degrade habitats through smothering, abrasion, and fragmentation, ultimately leading to mortality of benthic species, particularly corals (Donohue et al., 2001; Asoh et al., 2004; Chiappone et al., 2005). Large marine debris is known to transport nonnative biofouling species (Ghaderi and Henderson, 2013; Calder et al., 2014; Carlton, 2015). Furthermore, it can negatively affect marine wildlife through entanglement, which can harm fish (Romeo et al., 2015; Cannon et al., 2016), birds (Wilcox et al., 2015), turtles (Nelms et al., 2016), marine mammals (Henderson, 2001; Derraik, 2002; Attademo et al., 2015), and invertebrates (Donohue et al., 2001; Asoh et al., 2004; Setälä et al., 2016). Chemical contaminants can be transported, leach into the environment, and transfer to wildlife (Rios et al., 2007; Teuten et al., 2009). All of these threats can compromise the balance of marine ecosystems, resulting in costly control efforts, cleanups, and negative economic impacts (Mouat et al., 2010).

Hawaii historically has the highest reported debris accumulations for United States' Pacific Ocean coastlines (Ribic et al., 2012a). This influx of marine debris is attributed to the state's proximity to the North Pacific Subtropical Gyre (Howell et al., 2012) and the Subtropical Convergence Zone (Ribic et al., 2012a). In addition, the 2011 Tōhoku tsunami swept millions of metric tons of large detritus into the ocean (Headquarters for Ocean Policy, 2013). This litter began arriving on U.S. shores in the winter of 2011–2012 and continued to arrive in Hawaii through 2016 (Carlton et al., 2017). Multiple pieces of Japanese tsunami marine debris (JTMD) were found to host non-native species, representing a potential vector of invasive introductions (Derraik, 2002; Choong and Calder, 2013; Gewin, 2013; Calder et al., 2014; Carlton et al., 2017). Thus, marine debris accumulation in Hawaii is a pressing threat, especially following a major natural disaster.

Our understanding of marine debris accumulation patterns and composition in Hawaii is limited both in scale and scope. Previous studies focused on Oahu (Ribic et al., 2012a), Hawaii Island (Carson et al., 2013), Maui (Blickley et al., 2016), Midway Atoll (Ribic et al., 2012b), and Kure and Pearl and Hermes Atolls (Dameron et al., 2007). Hawaii-based studies have also addressed specific debris types in the state, such as derelict fishing gear (Donohue et al., 2001; Boland and Donohue, 2003; PIFSC, 2010), and plastics (Corcoran et al., 2009; Cooper and Corcoran, 2010; Kwon et al., 2014; Young and Elliott, 2016). There has not been a comprehensive quantification of marine

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debris in the main Hawaiian Islands (MHI) to date. The challenges of such an effort in the MHIs include the shorelines' ruggedness and inaccessibility, and the extensive distance that must be reconciled with time available and the level of detection and detail. A large-scale and systematic surveillance and spatial analysis technique is required to successfully map the entirety of the MHI.

This effort is the first study to use orthorectified aerial imagery to identify and categorize marine macro-debris in the MHI. The aim of this study was to (1) locate, quantify, and categorize debris, (2) map hot spots (areas of high debris accumulation), and (3) find and physically verify putative JTMD vessels. Creating a comprehensive baseline of marine macro-debris patterns across the entirety of the MHI assists both managers and community groups in prioritizing future debris removal efforts, particularly following major natural disasters in the Pacific Ocean.

2. Materials & methods

2.1. Aerial imagery collection and processing

To collect coastal imagery, aerial surveys were conducted over the coastlines of the main Hawaiian Islands of Niihau, Kauai, Oahu, Molokai, Lanai, Maui, Kahoolawe, and Hawaii (Fig. 1) using a Cessna 206. Sixteen missions were flown on fourteen separate days from August to October 2015 during optimal weather conditions to minimize cloud cover and avoid high winds and turbulence (Table 1). Areas where flight restrictions apply, such as military bases and airports, were excluded from the imagery collection process.

Photos were collected at a target overlap of 60% and an altitude of 610 m above ground level (AGL). This produced the final orthorectified imagery mosaics at 2 cm ground sample distance (GSD) and covered a swath of 300 m. The remote sensing system (Icaros IDM600) included two DSLR cameras (Canon EOS 5DS R) and one medium format aerial camera (Phase One P65 +) mounted on a three-axis gyro-stabilized gimbal to ensure that all photos were taken within 4 degrees of roll, pitch and yaw. Real-time, differentially corrected GPS data was obtained through the OmniSTAR satellite-based augmentation system. Raw camera data was converted and corrected for lens distortion, variable lighting, and systematic noise reduction or image sharpening using Capture One Pro (Phase One, 2015).

The aerial photos were synchronized with corresponding data on latitude, longitude, altitude, roll, pitch, and yaw. A standard photogrammetric aerial triangulation routine was performed in Icaros Photogrammetry Suite (Icaros, Inc., 2014). Each block of data was then

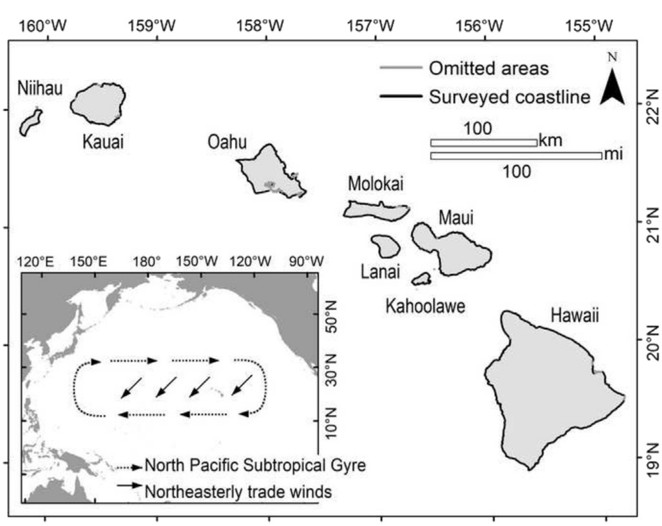

Fig. 1. Site map of the main Hawaiian Islands (MHI) showing the survey area (main) and location with respect to the North Pacific Subtropical Gyre (inset).

Table 1
Aerial survey dates. Flight time estimates are based on shoreline length and target ground speed. Total number of hours was 38.9, which includes time spent in transit from airports, delays, missed attempts due to weather conditions and air traffic, and extra passes required over complex shorelines.

Island	Shoreline (mi)	Dates surveyed	Estimated flight times (h)
Hawaii	392	Aug 7–9; Sept 1	4.1
Maui	192	Sept 7	2
Oahu	237	Sept 24	2.4
Molokai	119	Sept 23–24	1.2
Kauai	125	Oct 5–7	1.3
Lanai	58	Sept 9	0.6
Niihau	52	Oct 6	0.5
Kahoolawe	43	Sept 8	0.4

processed to obtain a within-model root-mean-square error (RMSE) of 1.5 m. Since only data from the aircraft's positions in the air was used without any ground control points, horizontal position errors ranged between 8 and 10 m. Finally, the imagery was color balanced and dodged to create a seamless mosaic and exported into uncompressed GeoTIFF tiles in the NAD 1983 UTM Zones 4N and 5N reference systems to correspond with existing GIS data layers. To ensure systematic analysis coverage, the imagery tiles were divided into numbered 1.6 km segments of coastline, which were overlaid onto the mosaics as a line shapefile in ArcGIS (ESRI, 2011). Out of the 1223 segments, imagery for 122 segments (10%) was not analyzed due to blurring or gaps resulting from airspace restrictions.

2.2. Marine debris analysis

Prior to detailed examination of the data, all analysts calibrated their efforts by processing the same set of imagery spanning approximately 76 km of coastline and comparing results. Data discrepancies were discussed among them to improve consistency and protocols were updated accordingly. In addition, randomly selected segments representing 20% of each island's coastline were re-analyzed to assess consistency among analysts and calculate a survey error associated with macro-debris detections.

The team visually panned through the imagery tiles and assigned every discernable debris item with a unique identification number. ArcGIS software (ESRI, 2011) was used to determine the latitude and longitude of each item. Eight categorical classifications (Table 2) were developed based on categories in Lippiatt et al. (2013) and the Alaska Department of Environmental Conservation tsunami debris aerial surveys (DEC, 2015). Analysts then recorded the macro-debris category by using photographic examples and visual characteristics such as shape and color for comparison (Fig. 2). Features, such as straight edges, spherical or conspicuous shape, and bright colors, assisted in the identification and classification of debris items. Items that could not be clearly identified in any of the eight categories were classified as "inconclusive." Those items that could be identified, but did not fit into the pre-determined categories, were classified as "other."

In addition, the ArcGIS measuring tool was used to determine the visible surface area of macro-debris items. Area measurements were grouped into four size classes: very small ($< 0.5\ m^2$), small ($0.5–1.0\ m^2$), medium ($1.0–2.0\ m^2$), and large ($> 2.0\ m^2$). Image resolution allowed for visual recognition of items as small as approximately $0.05\ m^2$. However, if a smaller debris item could be confidently detected, it was recorded. The 1.6 km segments were then categorized by debris density. To create the hotspots maps, the segments were regrouped into 8 km lengths to improve visual usefulness at a statewide scale, and any individual 8 km segment containing 100 debris items or more was considered a hotspot of debris accumulation.

Table 2
Descriptions of debris material categories used during analysis; debris categories adapted from Lippiatt et al. (2013) and Alaska DEC tsunami debris aerial surveys (2015).

Category	Description
Plastic	Any items made from plastic (with the exception of nets, line and buoys/floats) as well as plastic fragments; usually identified by bright colors and/or sharp edges
Buoys and floats	Any float used for mooring, as a buffer for boats, marking a channel, or fishing; can be plastic, glass, rubber, foam or metal
Nets	Any netting or woven line
Line	Single pieces of rope, fishing line, tangled rope, string, twine, and any other type of rope that is not woven into netting
Tires	Full tires and tire treads
Foam	Includes flotation, insulation, and packaging material
Other	Items consisting of processed wood, metal, or cloth, as well as vessels and vessel fragments that appear abandoned or derelict
Inconclusive	Items that were identified as marine debris, but could not be confidently classified into a material category

2.3. Physical inspection

Abandoned and derelict vessels (ADVs) were prioritized for on-the-ground physical inspections to verify detected vessel positions in the aerial imagery. This debris class was surveyed because managers considered ADVs as a potential navigational safety hazard and risk to the marine environment that should be assessed as quickly as possible, and because the status of some vessels as abandoned could not always be determined from the imagery (Fig. 3). Additionally, if an ADV could be identified as JTMD, it would be considered an item of cultural significance.

ADV inspections were conducted approximately four to eight months after aerial surveys, as resources were not available to conduct simultaneous on-the-ground surveys of all macro-debris categories during the aerial imagery collection process. Moreover, flight plans were dependent on variable weather conditions and required flexibility between islands. ADV surveys were conducted on Lanai in January 2016 and on Kauai, Molokai, Maui, Oahu, Hawaii Island, and Niihau in May 2016. Niihau vessels were assessed through an intermediary island resident. Kahoolawe was omitted as no vessels were found in the aerial imagery. Physical inspections on the other six islands entailed in-person surveys at the vessel coordinates gathered from the aerial imagery analysis using a Garmin GPSMAP® 78 with < 10 m GPS accuracy. If no vessel was found, the area was surveyed for 500 m in either direction along the coastline for the vessel or putative vessel fragments. Located vessels were inspected for signs of boat registration numbers and JTMD status.

To evaluate the possibility of the vessel being abandoned according to HI Rev Stat § 200-41 (2011) and/or JTMD, vessels were compared between the 2015 aerial imagery and historical satellite imagery retrieved from Google Earth© v 7.1 (Google, Inc., 2016). Vessels that remained in the exact position for more than one year in the historical imagery were classified as ADVs. If a vessel was present in satellite imagery prior to the March 2011 tsunami, it was excluded as potential JTMD. Identified vessels that had arrived afterwards were compared to the 23 confirmed JTMD vessels reported in the State of Hawaii for common characteristics (Fig. 3), namely a blue hull with white siding and the presence of kanji, and to images of small vessels affected by the Tōhoku tsunami (Suppasri et al., 2014). Vessel information was submitted to the Consulate General of Japan in Honolulu to compare the registration number or other identifying writing with boating records in their country. Final confirmation as JTMD was relayed to the National Oceanic and Atmospheric Administration (NOAA) Marine Debris Office.

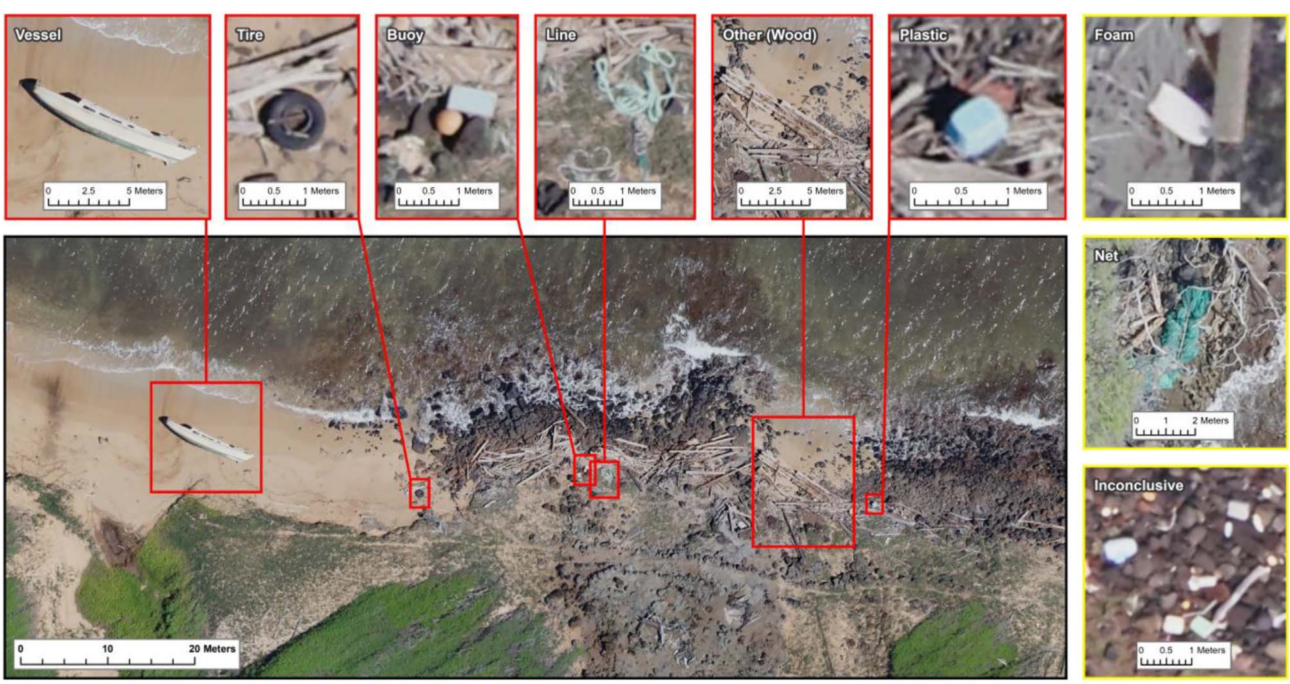

Fig. 2. Sample imagery from the analysis with categorized debris items representing each of the defined categories. Items in red were identified within the selected sample imagery. Items in yellow were pulled from other sections of coastline to represent categories not included within the selected sample. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

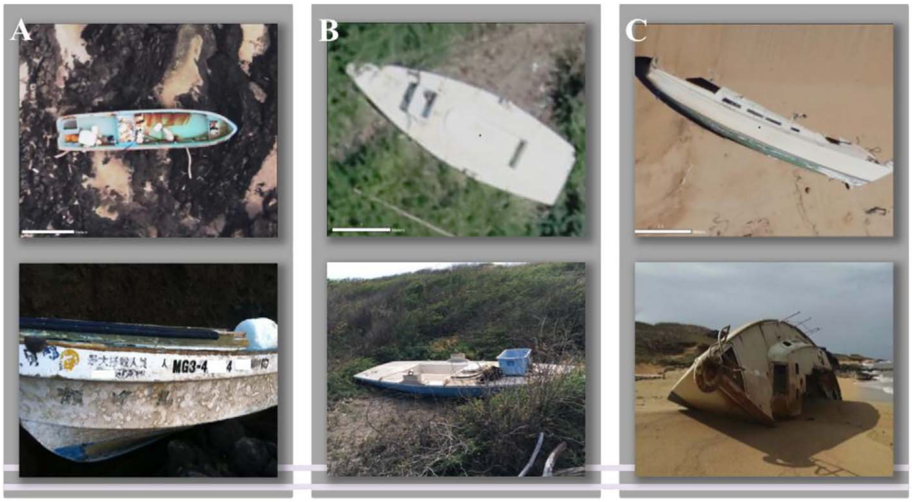

Fig. 3. Three sample vessels (A, B, and C) identified from the aerial imagery (top) and their corresponding in situ ground truth images (bottom). Vessel A was suspected JTMD due to similar colors and shape with previously confirmed JTMD vessels, and was later confirmed using its hull registration number (redacted for privacy). Vessel B was identifiable as a vessel, but it wasn't clear until ground truth observations that it was not an abandoned or derelict vessel (ADV). Vessel C was not suspected as Japanese tsunami marine debris but appeared to be an ADV due to its position on its side. Ground truth observations confirmed it as an ADV.

3. Results

3.1. Analysis team accuracy

Observer calibration resulted in comparative analysis of 227 coastline segments. 58% were given the same density rating during the calibration. While there was variation in the actual number of debris items identified between original and calibration analysis, the mean difference in item count was only 6.5, with a standard error of 0.98. The majority (69%) of segments originally rated as 0 (no debris found) maintained this rating throughout the calibration process, with the magnitude of error between observers increasing with higher debris counts.

3.2. Abundance and location

A total of 20,658 individual macro-debris items were identified statewide, hereinafter referred to as the "total debris" (Table 3). Niihau, the smallest of the MHI, had the greatest quantity of macro-debris, with 7871 items detected (38% of the total debris). Each of the other islands surveyed contributed 14% or less to the total debris, with Oahu having the lowest debris count of 984 debris items (5% of the total debris). Debris was primarily concentrated on windward (north- and east-facing) shores (76% ± 7.1% SD of the total debris), with leeward (west-facing) shores having the least (8.9% ± 4.8% SD of the total debris).

Table 3
Summary of segment and debris density details for each island surveyed. Each segment represents 1.6 km of coastline. Windward segments are those on north- and east-facing shores. Debris counts are of all identified macrodebris on an island, and percentages under total debris represent the proportion of debris count to the statewide total.

Island	All segments			Windward segments		
	Segments	Debris count	Total debris	Segments	Debris count	Total debris
Hawaii	398	2200	11%	140	1623	74%
Maui	192	1749	8%	13	1245	81%
Oahu	235	984	5%	45	639	72%
Molokai	120	2878	14%	18	2212	87%
Kauai	125	1849	9%	83	1331	71%
Lanai	58	1829	9%	47	1829	77%
Niihau	52	7871	38%	20	6477	82%
Kahoolawe	43	1298	6%	60	1048	65%

3.3. Type and size

The most common macro-debris categories were those made primarily from plastic polymer, including nets and line (22%), buoys and floats (11%), foam (3%), and all other plastics (47%). Composite items such as tires (5%) and those classified as "other" (6%) variably contained plastic polymer and were counted separately. Macro-debris categorized as "inconclusive" accounted for 7% of the total debris.

The majority (86%) of total debris sizes were very small ($< 0.5\ m^2$), true of at least 70% of the debris on any one island. The sizes of the remaining total debris were 6% small ($0.5–1.0\ m^2$), 4% medium ($1.0–2.0\ m^2$) and 4% large ($> 2.0\ m^2$). This relative abundance of each size class was consistent across all eight of the MHI.

3.4. Physical inspections of vessels

52 vessels were detected in the aerial imagery, 28 of which were selected for on-the-ground surveys based on the historical satellite imagery. The vessels that were not included in this ground truth process were determined to be actively used and not ADVs (18), inaccessible (5), or confirmed missing (1). In total, 30 ADVs were identified and confirmed from the analysis.

Ten putative JTMD ADVs were identified. Six of these vessels could not be located within 500 m of their last known position, two of which were recovered on nearby coastlines in fragments but positively identified using boating registration numbers and prior on-the-ground assessments by resource managers.

4. Discussion

4.1. Marine macro-debris detection

The methods used in this study advance the ability of researchers to systematically quantify marine macro-debris over an expansive coastline in several ways. The imagery mosaic allowed the team to pan through a seamless coastline map of imagery rather than view each image individually, saving time and effort and reducing the chance of duplicate observations. Orthorectification, the process of correcting the effects of camera tilt, lens distortion, and topographic relief, allowed the analysts to make consistent measurements of debris size. Overall the study achieved statewide coverage, short data collection times, high resolution detail, and allowed for repeated analysis as needed.

Alternate imagery collection methods did not have the capabilities and/or cost-effectiveness required for this study. At the time, satellite imagery provided wider coverage and was more cost-effective to acquire than products used here, yet data products did not provide fine

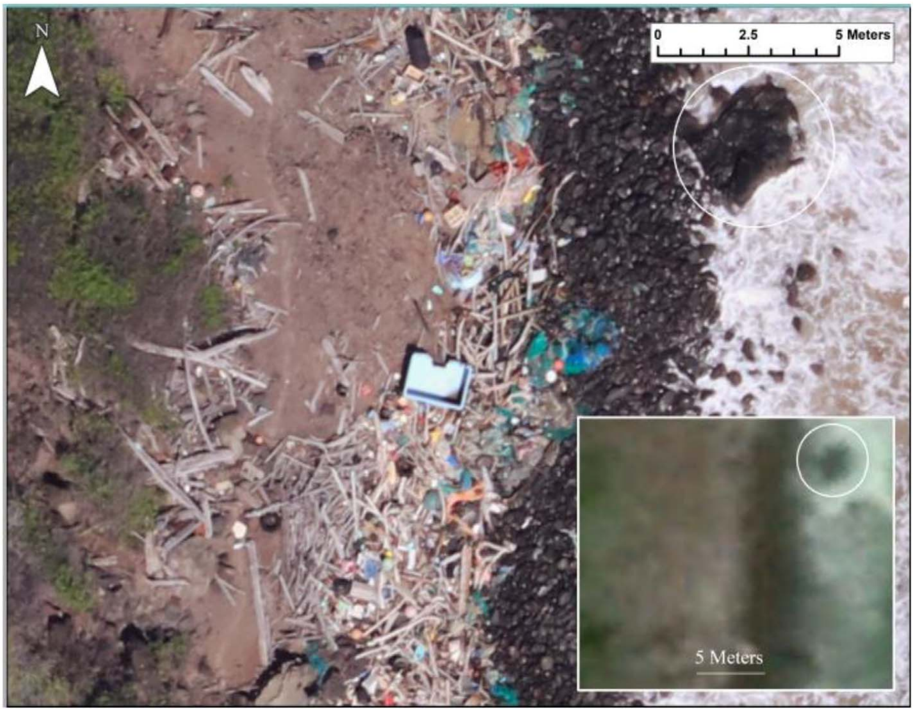

Fig. 4. Sample high resolution imagery from the Niihau coast used in this study (main) and sample Google Earth satellite imagery (21.953509, −160.076328) from 2014 showing the same stretch of coast (inset).

enough resolution to detect individual debris items accurately (Fig. 4). Even very high resolution (VHR) satellite imagery was limited to open landscapes, high contrast between target and background, and large target size (LaRue et al., 2017). The highest resolution available at the time of this study was from commercial satellite imagery. WorldView-3 was, at best, 31 cm in the panchromatic band or 1.24 m in the multispectral bands (Fretwell et al., 2017).

Conversely, low-altitude monitoring methods, such as unmanned aircraft systems (UAS), offer ultra-high resolution imagery, but their operational use over large expanses of coastline is hampered by FAA restrictions. UAS are only permitted to fly under 400 ft. (∼122 m) above ground level. This restrains the area covered per photo, which substantially increases the time required for image capture and processing. Moreover, UAS pilots must maintain visual line of sight, which would present difficulties at remote and inaccessible shorelines. Finally, it is prohibited to fly UAS over people, which vastly limits where and when flights can be conducted.

There are alternative marine debris surveillance approaches that provide high resolution imagery, such as in-flight observations (PIFSC, 2010) and oblique angle photography from fixed wing aircraft (Kataoka et al., 2017), balloon (Nakashima et al., 2011), and webcam (Kako et al., 2010; Kataoka et al., 2012). However, they are limited by the lack of consistency in camera altitude, angles and position at the moment of each photo's capture, which can reduce the measurement precision and accuracy of the resulting imagery (Magome et al., 2007; Kako et al., 2010; Kataoka et al., 2012, 2017).

However, the present study shares many limitations with the aforementioned methods. With top-down photography, only the superficial layer of debris is detectable and vegetation can obscure or block debris underneath it (Kataoka et al., 2017; LaRue et al., 2017). Additionally, the resolution is still limited such that detection is achievable down to 0.05 m^2, but categorization proved challenging below 0.5 m^2. Accumulation estimates of all marine debris are therefore likely underestimated (Kataoka et al., 2017), and lower contrast items are more likely to be overlooked at the smallest size classes (LaRue et al., 2017). Since these smaller size class marine debris typically consist of plastics (Gregory and Ryan, 1997; Morét-Ferguson et al., 2010; Martins and Sobral, 2011), the high proportion of macroplastics (> 20 mm; Barnes et al., 2009; Ryan et al., 2009) detected in our study is also likely underestimated, though it is consistent with other studies (Gregory and Ryan, 1997). Our mapping systems are already outdated and could be replaced with newer, more efficient methods. Semi- or fully-automated image analysis algorithms were beyond the scope of this study, but there is a strong case for object-based classification algorithms that mimic human cognition skills of identifying spatial characteristics like texture, context, and shape (Blaschke, 2010). This would require significant resources to produce one time, yet could be easily applied to future large-scale/long-term coastal monitoring data.

It's also important to note that this study did not account for beach cleanup efforts in the identification of marine macro-debris hotspots. Beach cleanups are conducted year-round throughout the MHI and constitute a considerable removal effort. For example, the Hawaii Environmental Cleanup Coalition removed over 98,000 kg of marine debris in 2016 (HECC, 2016). For these reasons, the study should be considered an underestimate, but is indicative of the categorical makeup, size, location, and total debris present on Hawaii's coastlines.

4.2. Usefulness for targeted cleanups, monitoring, and ADV removals

The analysis confirmed that most macro-debris aggregations, or “hotspots,” were located on windward (north- and east-facing) shores (Fig. 5). Similar to findings of previous studies on the Great Barrier Reef (Critchell et al., 2015) and the MHI (PIFSC, 2010; Ribic et al., 2012b; Blickley et al., 2016), our results indicate a pattern of macro-debris accumulation resulting from prevailing wind and current forces that drive the movement of marine debris in the Pacific Ocean (Fig. 1). Many of these hotspots, like those on Niihau or Molokai's north shore, are extremely remote and largely inaccessible to monitoring and removal efforts. By identifying areas of high debris concentrations, resource managers and cleanup groups can focus their efforts at these challenging locations with prior knowledge of expected debris accumulations.

The present study's methodology could be applied to accumulation surveys of macro-debris elsewhere, with on-the-ground surveys implemented in conjunction with flights to better gauge accuracy and precision, as done in other studies (Kataoka et al., 2012, 2017; Fretwell

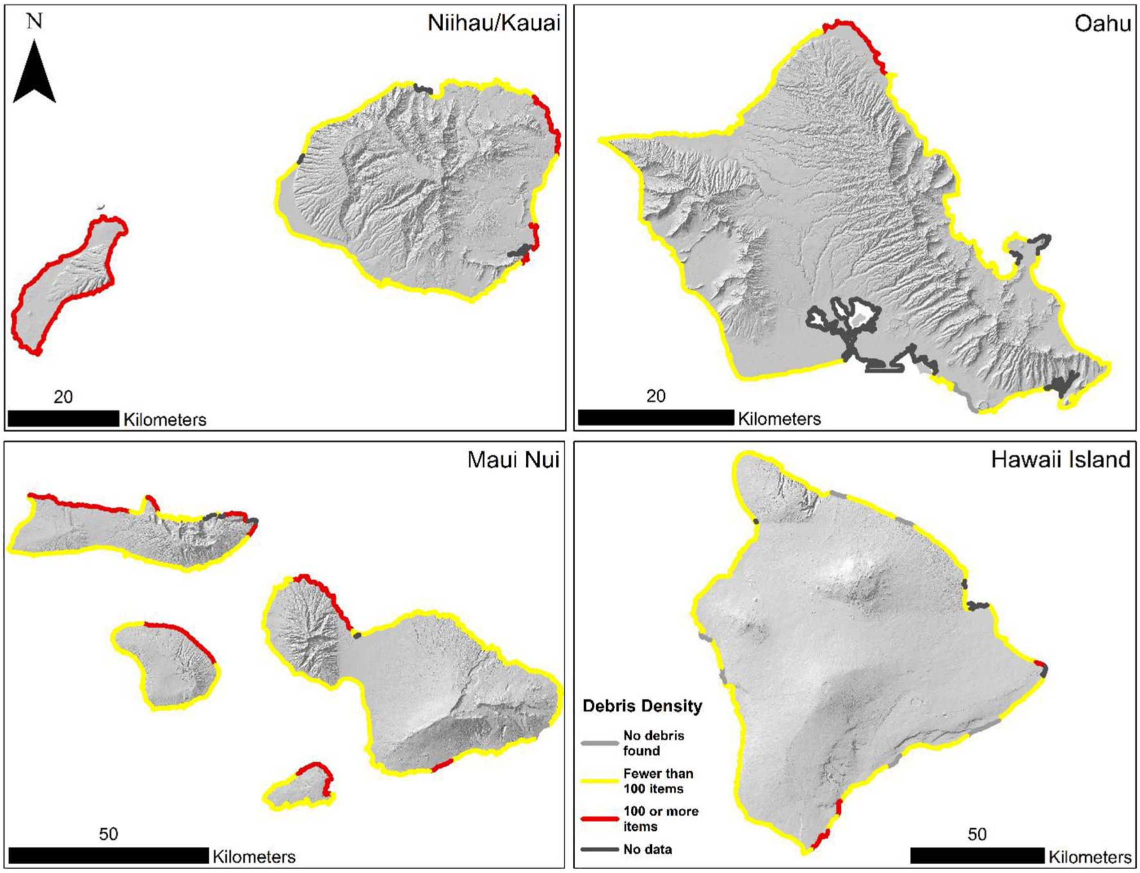

Fig. 5. Density and distribution of debris on the main Hawaiian Islands. Debris densities originally observed in 1.6 km segments were adjusted into 8 km segments for the purposes of the statewide maps. Segments with 100 or more items are highlighted in red as "hotspots," or areas of high marine debris accumulation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al., 2017). Focused reassessment of hotspots could help study debris accumulations over time, and repeated surveys will strengthen the baseline data so that the methodology can be most effectively applied immediately following natural disasters to detect any potential pulses is debris quantity and composition.

Our findings suggest that using the aerial imagery alone was insufficient to quantify ADVs on coastlines (Fig. 3), as five of the vessels identified as potential ADVs were in fact still in use. The analysis successfully improved detection of JTMD ADVs by identifying an additional eight vessels that were unreported (DLNR, 2016, personal communication). Resource managers prioritized JTMD vessels across the northern Pacific Ocean due to the high incidence of nonnative aquatic species biofouling (Gewin, 2013; Carlton et al., 2017). Detection is therefore time-sensitive to dispose of vessels quickly and to collect any live biofouling samples. Furthermore, we found that within four to eight months of photographing the vessels, six of the ten reported JTMD ADVs were lost. These beached vessels are exposed to tidal conditions and can be swept back out to sea within weeks of their discovery, further compounding the urgency of early detection and response for resource managers.

5. Conclusions

Considering the transient nature of debris continuously entering marine environments throughout the Pacific Ocean, it will require long-term comprehensive management to remove this detritus (Coe and Rogers, 1997). The 2011 Tōhoku tsunami brought increased attention to marine debris arriving throughout the Pacific Ocean and the potential consequences of debris pulses following natural disasters. This study could be a viable approach for identifying and assessing marine debris loads and has particular applicability following natural disasters and along rugged and/or inaccessible coastlines.

The methodology in this assessment documented that marine debris continues to be a problem far greater than JTMD in Hawaii. The sources of marine debris can be influenced by many factors (Browne et al., 2015). In most cases, litter is attributed to a combination of land- and ocean-based nonpoint sources, including fishing and boating materials (Merrell, 1980; Whiting, 1998; Walker et al., 2006; Storrier et al., 2007; Ariza et al., 2008; Ribic et al., 2012b), rather than a specific natural disaster event like the 2011 Tōhoku tsunami. Locating sources and sinks is essential for ongoing management (Donohue et al., 2001; PIFSC, 2010; Ribic et al., 2012a, 2012b; Blickley et al., 2016). This study focused on just one part of the long marine debris transport and breakdown process, describing the categorical composition of macrodebris and identifying hotspots. These findings help to establish a structured protocol for mapping and monitoring debris when it is most detectable, on land, and when cleanup groups, communities, and resource managers can prevent it from reentering the marine environment.

A storymap version of our findings is available through the State of Hawaii Office of Planning: http://arcg.is/29tjSqk.

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