Available online at www.sciencedirect.com

ScienceDirect

Marine Pollution Bulletin 54 (2007) 423–433

MARINE POLLUTION BULLETIN

www.elsevier.com/locate/marpolbul

Marine debris accumulation in the Northwestern Hawaiian Islands: An examination of rates and processes

Oliver J. Dameron [a,*], Michael Parke [b], Mark A. Albins [a], Russell Brainard [b]

[a] *Joint Institute of Marine and Atmospheric Research and NOAA Fisheries Pacific Islands Fisheries Science Center, 1125B Ala Moana Boulevard, Honolulu, HI 96814, USA*

[b] *Pacific Islands Fisheries Science Center, NOAA Fisheries, 1125B Ala Moana Boulevard, Honolulu, HI 96814, USA*

Abstract

Large amounts of derelict fishing gear accumulate and cause damage to shallow coral reefs of the Northwestern Hawaiian Islands (NWHI). To facilitate maintenance of reefs cleaned during 1996–2005 removal efforts, we identify likely high-density debris areas by assessing reef characteristics (depth, benthic habitat type, and energy regime) that influence sub-regional debris accumulation. Previously cleaned backreef and lagoonal reefs at two NWHI locations were resurveyed for accumulated debris using two survey methods. Accumulated debris densities and weights were found to be greater in lagoonal reef areas. Sample weight-based debris densities are extrapolated to similar habitats throughout the NWHI using a spatial 'net habitat' dataset created by generalizing IKONOS satellite derivatives for depth and habitat classification. Prediction accuracy for this dataset is tested using historical debris point data. Annual NWHI debris accumulation is estimated to be 52.0 metric tonnes. For planning purposes, individual NWHI atolls/reefs are allotted a proportion of this total.

Keywords: Marine debris; Derelict fishing gear; Accumulation rate; Coral reefs; Northwestern Hawaiian Islands

1. Introduction

Marine debris, specifically derelict fishing gear, represents a significant and persistent threat to the wildlife and coral reef ecosystems of the Hawaiian Archipelago (Fig. 1), including the remote Northwestern Hawaiian Islands (NWHI) and the more populated main Hawaiian Islands (Donohue et al., 2001, 2002; Henderson, 2001). The NWHI reefs have been reported to contain extraordinarily high densities of derelict fishing gear (Kubota, 1994; Donohue et al., 2001; Boland and Donohue, 2003; Pichel et al., 2003). Lost and abandoned fishing gear, primarily large trawl and drift nets, float into the region and come to rest within the more protected, low-energy, shallow water environments inside barrier reefs of the NWHI. During 1996–2005, an extensive multiagency debris removal program led by the National Marine Fisheries Service (NMFS) removed 492 metric tonnes (MT) of derelict fishing gear (Friedlander et al., 2005) from various sites within the NWHI. With the completion of the 2005 marine debris field season, most shallow benthic habitats (<10 m) thought to contain high densities of debris have been surveyed and cleaned. Beginning in 2006, NWHI marine debris removal efforts will be reduced to a maintenance mode aimed at keeping pace with new accumulations (Brainard, personal communication, 2006). To develop an efficient and effective program to address ongoing debris accumulation, it is necessary to obtain some understanding of the rates and processes associated with the accumulation of derelict fishing gear in the NWHI.

To identify reef areas in the NWHI predisposed to high debris accumulation densities, we examine the relevant regional physical forcing mechanisms and outline the common properties of reefs that enhance the settlement of

* Corresponding author. Tel.: +1 808 983 3718; fax: +1 808 983 3730.
E-mail address: oliver.dameron@noaa.gov (O.J. Dameron).

0025-326X/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2006.11.019

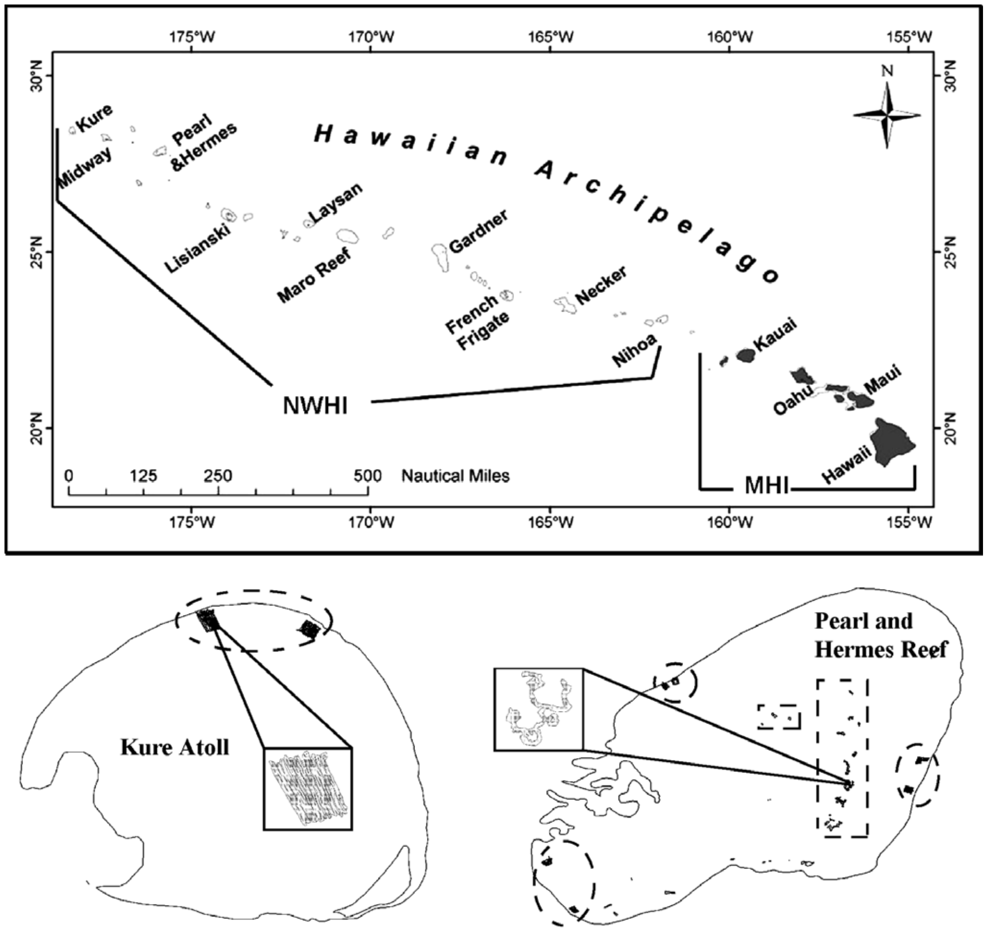

Fig. 1. Kure and Pearl and Hermes Atolls, shown enlarged, lie toward the northwestern end of the Hawaiian Archipelago. Accumulation survey locations are shown within the atolls, tow survey areas within dashed circles, and swim survey areas within dashed rectangles.

derelict fishing gear. These properties exist on a range of spatial (ocean-basin, atoll, sub-atoll) and temporal (inter-annual, seasonal, storm events) scales and must be considered accordingly. On the ocean-basin scale, a key physical forcing mechanism in the North Pacific is the convergence of surface waters in the subtropical convergence zone (STCZ), a phenomenon resulting from westerly winds in mid-latitudes and easterly winds in the tropics that shift on seasonal and interannual time-scales (Kubota, 1994; Brainard et al., 2000; Bograd et al., 2004). Kubota (1994) suggested this convergence zone acts as a mechanism for disproportionate accrual of marine debris in the area north of the Hawaiian Islands, a notion substantiated by aerial surveys (Veenstra et al., 2004). Models based on remotely-sensed observations of wind-stress curl, sea-surface temperature, and surface-chlorophyll levels have successfully predicted these areas of marine debris accumulation (Polovina et al., 2001; Pichel et al., 2003). Theoretically, the mean position of the convergence zone in the winter months, as it reaches its most southerly latitudes (~28° N), influences the annual accumulation rates in the NWHI, both between atolls/islands and within the archipelago as a whole. On the atoll scale, the primary geomorphological and physical characteristics of reefs that influence settlement of derelict fishing gear are shallow water depth, high-relief reef structure, and low exposure to significant wave energy (Donohue et al., 2002). These characteristics increase the likelihood that fishing gear will settle and determine a reef's suitability as potential 'net habitat'.

Marine debris accumulation rates have been quantified in several studies (Slip and Burton, 1991; Camacho-Arroyo et al., 1998; Henderson, 2001; Convey et al., 2002; Boland and Donohue, 2003). Boland and Donohue (2003) quantified accumulation rates, using number of nets per area, within nearshore habitats at three locations within the NWHI: Kure (KUR) and Pearl and Hermes (PHR) atolls and Lisianski Island (LIS). That study focused on areas where marine debris would most likely impact critically endangered Hawaiian monk seals (*Monachus schauinslandi*), and thus is inherently biased toward primary seal habitat rather than areas more prone to potential debris settlement. Termed 'High Entanglement Risk Zones (HERZ)', the focal areas of this previous study are situated near small, sandy islands and are largely composed of sand and low rugosity reef substrates, which allow debris to quickly traverse through these areas during the high-energy winter months. As such, Boland and Donohue (2003) did not examine the broader accumulation rates or patterns across the archipelago.

The current study uses marine debris survey data collected at KUR and PHR in 2005 to develop habitat-specific accumulation densities that should be applicable to similar habitat throughout the NWHI. We provide an estimate of annual accumulation within the NWHI that will be used as the baseline for planning future efforts aimed at reducing ecological impacts as new debris recruits to the area. In contrast to previous accumulation studies in the NWHI, this work provides weight-based estimates, rather than numerical count-based accumulation figures, and distinguishes separate debris accumulation rates for areas with different habitats.

2. Methods

2.1. Survey method

Marine debris surveys in 2005 were conducted at targeted KUR and PHR sites (Fig. 1) during summer months; historically a standard practice designed to take advantage of relatively quiescent summer conditions conducive to effective survey and removal operations. KUR is a nearly-enclosed atoll consisting of an eight kilometer-wide circular barrier reef surrounding Green Island and a shallow, primarily sandy lagoon. PHR is a kidney-shaped atoll approximately 30 km long and 13 km wide with breaks in the barrier reef on the west and northwest sides. PHR consists of several sand islets and a large lagoon containing erratic, shallow reef structures that rise from deeper lagoonal waters. Order-of-magnitude mean residence time estimates for KUR and PHR are 30 and 180 h, respectively (Hoeke, personal communication, 2006); inner-atoll circulation has yet to be described. At both locations, surveys targeted contiguous hardbottom habitats spanning the 0–30 ft depth range, but included incidental assessment of unconsolidated and vegetation-dominated benthic substrates and depths greater than 30 ft.

Two survey methods were used in the accumulation rate study as a result of their respective appropriateness in the two dominant survey habitats. Manta tow surveys were used in the relatively even-depth, contiguous backreef habitats, while non-linear swim surveys were used in the comparatively high-relief and patchy lagoonal reef habitats. The manta tow survey has been widely applied as an effective technique to survey underwater habitat and locate stationary items (Fernandes et al., 1990; Fernandes, 1990; Moran and De'ath, 1992; Boland and Donohue, 2003). The non-linear swim survey technique, first used for NWHI marine debris detection in 2002, was developed as a necessary alternative to towed diver surveys as field teams discovered significant quantities of derelict fishing gear accumulated in lagoonal, reticulated reef areas that were either too shallow or too irregular to be surveyed effectively with the manta tow technique. In the swim survey method, pairs of observers swim search patterns over the target reef with surface direction from observers aboard a small vessel. Although the effectiveness of swim surveys has not been quantified, this more intensive survey technique is considered to be more thorough than towed diver surveys.

2.2. Survey areas

Using a geographic information system (GIS), accumulation sites were randomly selected from areas previously surveyed and cleaned. Limited knowledge of the correlation between debris accumulation and temporally and spatially variable convergence patterns led to the selection of survey areas that had one-year accumulation when possible. In total, 80% of selected survey areas had been surveyed and cleaned one year prior, while the remaining sites contained debris accumulated over multiple years. A proportion of randomly selected areas were eliminated based on a set of predetermined characteristics. In atoll backreef areas surveyed by the manta tow technique, sections of incomplete and erratic previous coverage were eliminated in favor of areas with thorough and homogenous coverage. In lagoonal, reticulated reef areas surveyed by the swim survey technique, reefs more than 50 m wide were eliminated to ensure thorough coverage during accumulation surveys. The following additional criteria were imposed for logistical considerations: (1) sites for both swim and manta tow surveys were limited in size to approximate the amount of area that could be covered by one boat team (two divers, coxswain, data recorder/spotter) in one day; (2) if a randomly selected swim survey site was smaller than the area that could be covered in one boat-day, the nearest reef or reefs were added until the survey area approximated that coverable in one boat-day; (3) if a contiguous area was too large for one boat-day, the accumulation site was delimited to fit within the assumed coverage of one boat-day.

2.3. Data analysis

Calculations of debris accumulation are based on weights of individual net pieces and their position within a larger survey area. To arrive at individual net weights, a compacted volume was recorded for each piece of debris upon its removal from the habitat. Each boat-load was weighed upon return to the support vessel. Individual pieces of debris were allotted a percentage of this total boat-load weight, based on their proportional volume to the total volume of the boat-load. Personnel showed consistency in individual volume estimations and observations in the field confirmed a predictable volume to weight correlation ($n = 35$ boat-loads; mean = 318 kg/m^3; $r^2 = 0.923$).

A GIS overlay procedure identified areas of overlap among surveys during 2005 and surveys from previous years. A geographic grid, with 30 m × 30 m cells, provided the sampling frame to calculate debris density (by weight) per overlap area, with the density for each grid cell normalized to account for survey coverage within that cell. The sampling unit was chosen to be a unit of area small enough to respect the heterogeneity of debris distribution, yet large enough to keep the mean accumulation density from approaching zero. The mean weight-based densities for swim and tow surveys were calculated within sampled cells. Mean debris accumulation densities for backreef and lagoonal habitats are assumed to be equivalent for each atoll/reef in the NWHI.

2.4. Application of densities to the NWHI archipelago

To estimate yearly accumulation of marine debris for the reef ecosystems of the NWHI, we extrapolated observed sample marine debris densities across all NWHI reef areas with high net accumulation potential. Accumulation potential was based on three significant accumulation factors: bathymetry, benthic habitat, and energy regime. Pseudo-bathymetry data (Stumpf et al., 2002) and benthic habitat classifications (Holderied et al., 2002), derivatives of 4-m resolution IKONOS satellite imagery, were used to incorporate reef depth and habitat type, respectively.

Accounting for effects of energy regime was less straightforward. No NWHI-specific datasets exist to directly calculate energy regimes based on exposure to significant wave events. However, variation in reef morphology and coral composition has been linked to wave stress (Dollar, 1982; Storlazzi et al., 2001), thus the dominant coral species can be used as a proxy for wave stress. Storlazzi et al. (2001) modeled near-bed shear stress to show that the dominant Hawaiian coral species changes with increasing physical stress; *Porites compressa* dominates in low-, *Montipora* species in medium-, and *Porites lobata* and *Pocillopora meandrina* in high-energy reef environments. In another study, Dollar (1982) found that *P. meandrina* existed in areas too harsh for other species, while reefs completely protected from wave stress, such as lagoons, generally have monospecific stands of *P. compressa*. Studies of the coral community structure in the NWHI french frigate shoals (FFS), (PHR) have shown significant differences among habitats in the coral genera present among habitats (forereef, backreef, lagoon), with the higher-energy species more dominant in the forereef and backreef areas and *P. compressa* more dominant in lagoons (Kenyon et al., 2006; Kenyon et al.). The wave-correlated species variation suggests a difference between backreef and lagoonal circulation that is likely to have an effect on the settlement of derelict fishing gear. This difference in biotic community structure, considered alongside evident differences in overall geomorphic reef structure as well as differential exposure to wave-stress regimes, supports a thematic division between backreef (tow survey) and lagoonal (swim survey) areas in the application of debris accumulation rates.

The primary goals of NOAA's marine debris removal effort in the NWHI have been to (1) mitigate potential threats to the critically endangered Hawaiian monk seal (*M. schauinslandi*) by removing debris from specific monk seal habitat, and (2) mitigate potential threats to the overall ecosystem by removing as much debris as possible. These goals have resulted in selective searching for debris accumulations in a heterogeneous underwater environment. For example, suppose a 5-m deep area of patchy, reticulated reef was chosen for survey based on IKONOS imagery. If little or no debris was found during the survey and, based on prior knowledge, the reef was not of the type that catches significant debris; proximate areas with similar visual reef structure in the IKONOS imagery would be disregarded in favor of areas with higher expected density. As a result, reefs well within the limit of the 10-m working depth restriction, theoretically sites for debris accumulation, might never be surveyed because, given the objectives, such surveys would not be an efficient use of limited resources. Thus, estimates of NWHI debris accumulation in habitats less than 10 m, derived by extrapolating average debris densities from selected focal areas to the entire area within the depth restrictions would be biased upward.

To enable unbiased estimates of debris accumulation, we employed the IKONOS-derived NWHI habitat classification scheme (NOAA, 2003). The spatial bounds of potential debris accumulation areas were refined by benthic habitat class using a thematic generalization of this NOAA classification. In this generalization, all 'hardbottom' classes within an atoll/reef were grouped and reclassified into a single class; all 'unconsolidated', 'submerged vegetation', and 'other delineations' were eliminated as null data because of historically insignificant marine debris densities in these habitats (Boland, personal communication, 2006). By overlaying the reclassified reef structures with historical debris point location data (with 5-m buffers to account for GPS inaccuracy), we demonstrated the value of our reclassification method as an effective means to identify reefs of relatively high survey value. Areas designated as 'hardbottom' by our reclassification scheme had a high spatial coincidence with debris locations from past surveys. Fig. 2 depicts the process of refining the net habitat prediction model. The thematic habitat generalization is founded on the relationship between pixel appearance and site habitat; during extensive field time, we developed knowledge of actual habitat type based on the correlating visual characteristics in the imagery. In certain location-specific cases, a priori knowledge of actual benthic structure led to the exclusion of a 'hardbottom' class from the thematic generalization.

Since bathymetric surveys of the shallow waters of the NWHI have not been completed, bathymetric raster products developed from 4-m resolution IKONOS imagery (Holderied et al., 2002) were used to derive areas delimited by depth. Bathymetry for each $4\,m \times 4\,m$ pixel was estimated via an algorithm using the blue and green bands; output values are accurate to within 30% of LIDAR depths (Stumpf et al., 2002). Though NWHI marine debris surveys are logistically limited to a depth of 10 m, variable water visibility (as low as 5 m) does not allow surveys covering depths more than 5 m to have acceptable levels of detection accuracy. Thus, the 0–5 m depth range (1–15 ft, as dataset

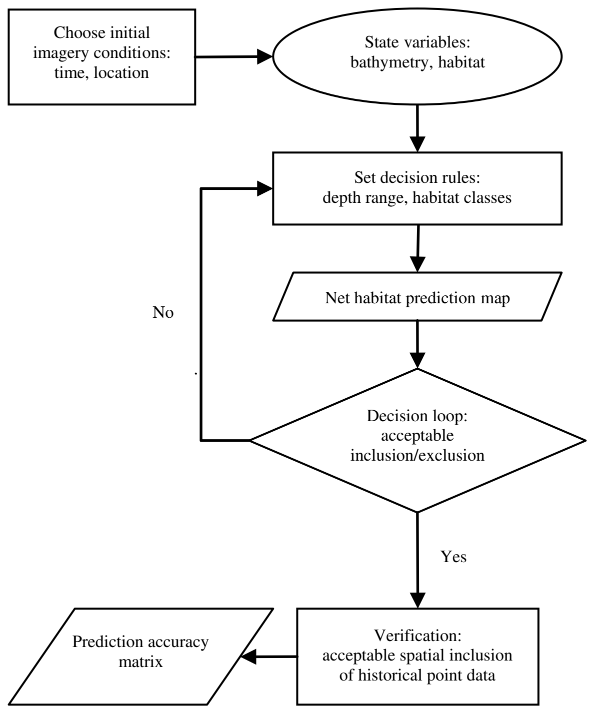

Fig. 2. Flowchart depicting the stages of development of the net habitat prediction model. Decision rules for a depth range and habitat classes were adjusted to maximize the inclusion and minimize the exclusion of debris point data collected during 2000–2005 debris removal efforts. The prediction accuracy matrix was produced for the final set of decision rules.

units are in feet) was chosen as the acceptable criterion for depth.

Both the habitat and bathymetry reclassifications were converted to polygons and a GIS clip function was applied to retain only areas of intersection between the acceptable depth and habitat products (see Fig. 3 example). For atolls/reefs with lagoonal areas (PHR, FFS, Maro Reef (MAR)), borders were digitized to delineate these areas from backreef areas. The final products, which incorporate habitat and depth and distinguish between backreef and lagoon, are used in association with the accumulation densities to yield estimates of annual accumulation by location.

2.5. Debris prediction

Testing the net habitat prediction model is essential to evaluating its utility for survey-area selection and the application of sample accumulation densities to the greater NWHI. A 5-m buffer was applied to all debris points, as marine geographic data recorded from a small boat platform amongst shallow reefs contain inherent spatial inaccuracy. Spatial error in the IKONOS imagery habitat derivative has been estimated to be within one 4-m pixel (NOAA, 2003); to account for this a 4-m buffer was applied to all predicted net habitat. This test analyzes the spatial relationship between historical point data and modeled net habitat, with the percentage of buffered net points intersecting the predicted net habitat being the resulting test statistic.

In addition to testing the ability of the net habitat model to correctly predict the presence of derelict fishing gear, we wanted to determine if the model over-predicted potential net habitat. To determine this, we used a prediction accuracy matrix, in which the possible combinations for each cell are (1) debris predicted and net found, (2) debris predicted and no net found, (3) debris not predicted and net found, and (4) debris not predicted and no net found. A 90 m × 90 m geographic grid was chosen as the unit of measurement that most adequately reflects the scale of the surveys; a finer grid produced excessive cells containing minimal survey coverage while a coarser grid grouped many unlike habitats. Spatial generalization serves to reduce the uncertainty in the data by identifying what is significant while still respecting the underlying habitat variation (Hunsaker et al., 2001). To avoid erroneous assignment of grid cells in areas of unknown debris abundance, only grid cells intersected by surveys are included. If a historical debris point was within a grid cell, that cell was counted as having net habitat. If any predicted net habitat intersected a grid cell, that cell was considered to be predicted.

3. Results

3.1. Accumulation densities

Based on 30 m × 30 m grid cells, the mean accumulation density in lagoonal areas of shallow, reticulated reef (swim survey) is approximately 2.5 times greater than accumulation in backreef areas with more homogenous, generally deeper bathymetric structure and closer proximity to a barrier reef (tow survey) (Table 1a). The difference of mean densities (kg/900 m^2) between backreef grid cells and lagoonal grid cells is not significant (student's *t*-test; $P = 0.09$). However, the variance of swim survey density is much higher due to both the higher number of nets per area and the greater and more variable weights. This is supported in Table 1b by the significant difference in average weight of nets (29.30 kg and 10.12 kg) found during swim and tow surveys, respectively ($P = 0.01$).

The annual estimated debris accumulation in the NWHI, calculated by extrapolating our sample accumulation densities to all predicted accumulation areas in the NWHI is 52.0 MT (Table 2). This table presents estimates of total annual debris accumulation at the atoll/reef level. Estimates were calculated by multiplying the mean sample accumulation rates (kg/km^2) for swim and tow survey habitat types by the total area of similar habitat at each atoll/reef location.

3.2. Debris prediction

The net habitat prediction graph (Fig. 4) shows the percentage of buffered net points (years 2000–2005) intersecting the buffered net habitat by location and survey type.

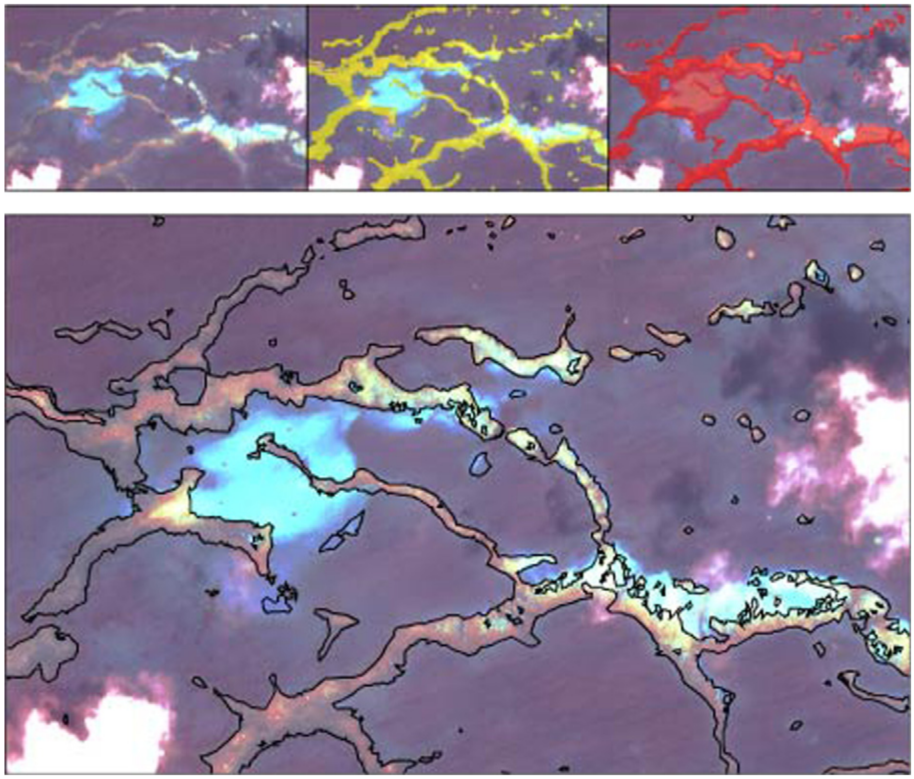

Fig. 3. Four-meter resolution IKONOS satellite imagery with GIS layer overlays. Bare imagery (top left), 'hardbottom' benthic habitats in yellow (top center), depths of 1–15 ft in red (top right), and the final net habitat product, after a GIS spatial clip, shown in black outline (bottom).

Table 1
Statistics for the two methods of evaluating characteristics of debris accumulation in backreef and lagoonal reef areas

	Backreef	Lagoon	Units
(a) Grid cell statistics			
Number of cells	1713	989	Count
Mean density	0.42	1.02	kg/900 m^2
Standard deviation	4.62	10.40	kg/900 m^2
Variance	21.35	108.21	(kg/900 m^2)^2
(b) Debris point statistics			
Count	58	55	Count
Maximum weight	160.00	227.00	kg
Mean weight	10.12	29.30	kg
Standard deviation	22.51	52.33	kg
Variance	506.7	2738.43	kg^2

The grid cell statistics (a) describe accumulated debris via a point-in-polygon method, normalized by surveyed area within each grid cell. Debris point statistics (b) describe the weight of individual debris points in the generalized reef types.

Table 2
Annual accumulation is calculated for each location based on the net habitat area and the accumulation rate for the corresponding reef type

Location	Habitat	Debris habitat area (km^2)	Accumulation rate (kg/km^2)	Accumulation per year (kg)
KUR	Backreef	5.87	445.57	2617
FFS	Backreef	10.19	445.57	4541
MID	Backreef	14.31	445.57	6377
MAR	Lagoon	9.93	1065.00	10,581
PHR	Lagoon	12.65	1065.00	13,477
PHR	Backreef	32.32	445.57	14,401
LIS	?	9.51	?	?
LAY	?	0.76	?	?
FFS	?	4.56	?	?
Totals	NA	85.29	3912.28	51,993.44

Question marks represent regions where neither the tow survey nor the swim survey model adequately describes the accumulation scheme.

With the exception of LIS (small survey area, small sample size), the success of the model in predicting areas where debris was actually found was much greater in reticulated lagoonal areas, with a positive prediction of 86% compared to 66% for backreef tow areas.

The total number of 90 m × 90 m cells with at least partial coverage during NWHI combined surveys from 2000–2005 was 21,668. The net habitat model included 94% of cells where debris was previously found. Areas within the reef systems that had not been surveyed were omitted from the accuracy assessment (Table 3). Derelict fishing gear was found in 25% of cells in which it was predicted. In other words, of 16,608 cells predicted as potential debris accumulation zones, debris had settled in 4097 of them. Predictions of no debris in areas previously surveyed were correct at a 95% level (4797 of 5060). The low overall accuracy for the matrix (41%) is believed to be a situational byproduct of the opportunistic survey methods.

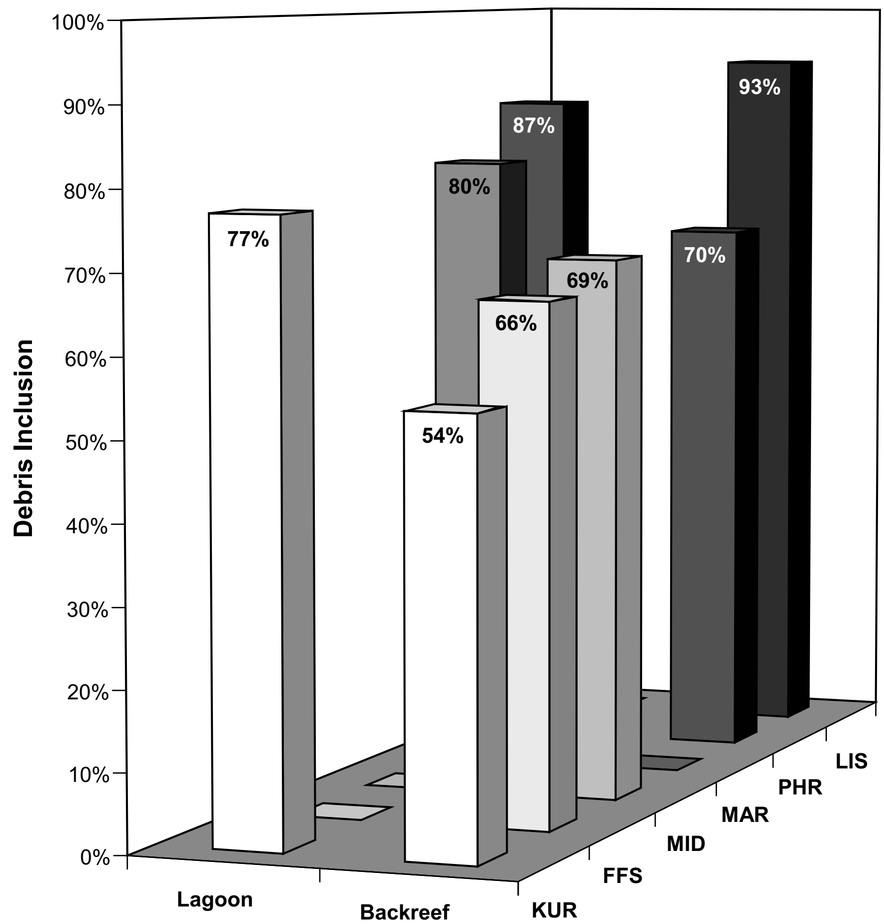

Fig. 4. Net habitat prediction graph depicting the percentage of historical debris points intersecting the net habitat prediction area.

Table 3
Prediction accuracy matrix for historical point data (left column) and IKONOS-derived net habitat prediction (top row)

Post-survey class	IKONOS-derived class		Total possible	Accuracy
	Net predicted	Net not predicted		
Net	4097	263	4360	0.9397
No net	12,511	4797	17,308	0.2772
Total	16,608	5060	21,668	–
Accuracy	0.2467	0.9480	–	0.4105

All cells included in this accuracy matrix contain area covered during marine debris surveys from 2000 to 2005.

4. Discussion

4.1. Discussion of grid cell values

Analysis of grid-based and point-based statistics calculated from accumulation surveys yielded similar patterns in the distribution and weights of derelict fishing gear. Debris accumulates in higher densities (numerical and weight-based) in low-energy lagoonal areas than in backreef areas. The nearly three-fold difference in average weight of debris fragments between low-relief backreef areas and relatively high-relief lagoonal reefs suggests that large fragments of fishing gear are forced through areas of high wave-stress into lower energy environments where entanglement and long-term settlement occurs. Higher debris density in reticulated lagoonal regions is likely a product of the parameters outlined earlier: shallow water depth, high-relief reef structure, and low exposure to significant wave energy, all characteristics found in lagoonal reefs at both PHR and MAR. Derelict fishing gear that passes through the initial reef barrier zones may drift until encountering a shallow, rugose reef where, without significant wave stress, it is allowed to become increasingly entangled. High variance values for grid and point statistics indicate that debris accumulation, in a spatial sense, is highly irregular; more than 90% of grid cells possessed no accumulated debris. Variability in weight statistics is also characteristic of debris accumulation, as a few debris pieces often account for most of the total weight collected in a field day (Table 1b).

4.2. Prediction accuracy matrix

Though the correlation between predicted and actual debris existence in the grid returned low overall map accuracy (41%), the model does show value in delineating areas of potential debris accumulation. A considerable number

(75%) of predicted debris areas, areas with benthic characteristics suitable for accumulation were found to be free of debris – a result of the highly irregular nature of debris distribution. This low accuracy is primarily because of the result-oriented objective of the marine debris removal project. Survey areas were selected using IKONOS imagery based on their likelihood of containing net that could be found and removed by divers. Overall prediction accuracy would be much higher if knowledge of net habitat was ignored and all area within an atoll/reef was sampled randomly during the surveys. The accuracy matrix provides relevant information about the utility of the model and the value in the prediction technique.

4.3. Annual accumulation estimate

Calculation of annual accumulation by location shows that tow survey habitat and swim survey habitat at PHR potentially have the highest and second highest annual accumulation totals, respectively. As seen in the pie chart in Fig. 5, PHR is predicted to receive 54% of the yearly accumulation in areas of the NWHI considered by the current model. This suggests that PHR will require the most dedicated marine debris removal effort in the future. This prediction figure is supported by the fact that 294 of the total 492 MT (60%) of derelict fishing gear removed from the NWHI through 2005 have been removed from PHR. In addition to possessing considerably more net habitat than any other atoll/reef, PHR has an extensive barrier reef that surrounds a reticulated reef system, creating an expansive low-energy environment. The only other location with a similar low-energy interior environment is MAR which, we estimate, has the third highest annual accumulation rate among the NWHI habitats. Though the other three locations (Midway (MID), FFS, KUR) show considerably lower annual accumulation, likely as a result of their relative lack of reticulated reef areas and overall lack of potential net habitat, each location has been proven to accumulate substantial quantities of debris (114.3 MT removed during 1996–2005 period). While these locations may require a lower effort level to keep up with annual accumulation than will PHR and MAR, removal efforts should remain proportional to the estimated share of the annual accumulation by location (Fig. 5).

The NWHI annual accumulation figure of 52.0 MT does not include sections of reef at LIS, FFS, MAR, and a small area of reef at Laysan Island (LAY) that are characteristically dissimilar to both lagoon and backreef reef types. At LIS, surveys in the relatively small HERZ on the east side of the island have shown that numerical debris densities are lower than the tow survey densities at other locations. Additionally, in Neva Shoals (south of Lisianski Island), where the reef is highly reticulated and the model predicts considerable debris accumulation, preliminary surveys have been debris-free. This discrepancy between predicted and actual accumulation potential is due, at least in part, to the failure to categorize habitat to the sub-level classification. Given the current habitat classification at LIS we were unable to exclude certain 'hardbottom' classes in our reclassification of likely debris habitat (performed at

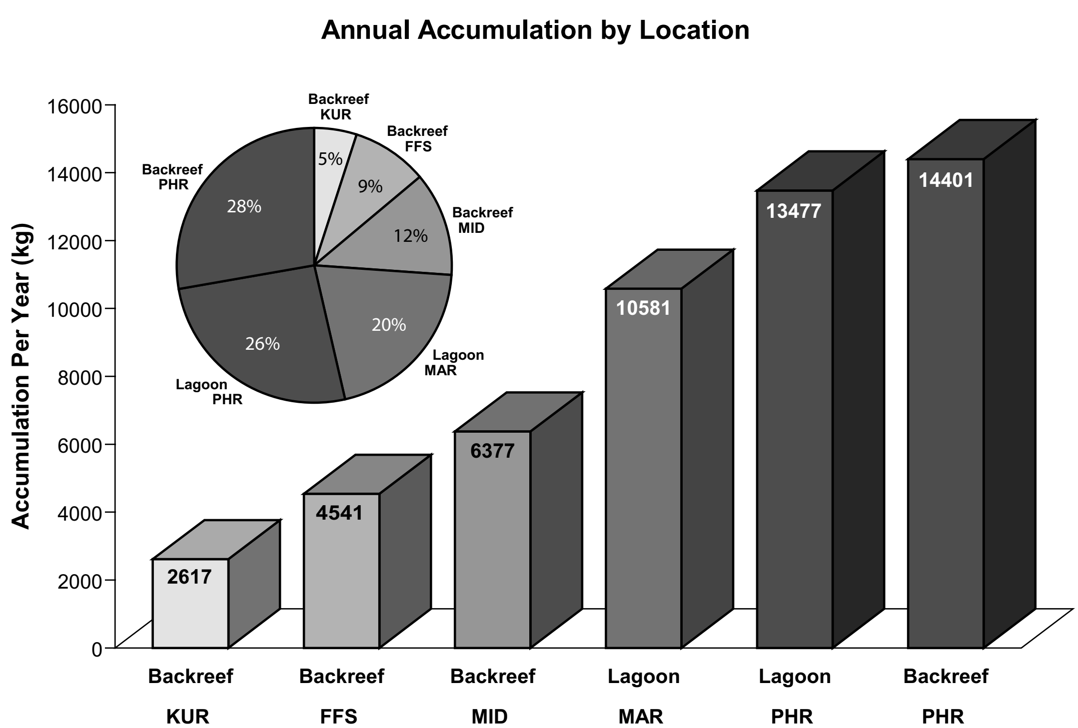

Fig. 5. Predicted annual accumulation of derelict fishing gear for each location where the net habitat prediction model is deemed to be applicable. The bars depict the estimated weight of accumulated debris per year; the pie chart shows the estimated proportional accumulation of each location to the total annual NWHI debris accumulation.

other locations based on site-specific knowledge). The inability to classify these areas as either backreef or lagoonal led to the exclusion of the reef system surrounding LIS from the total NWHI annual accumulation estimate. At FFS, interior regions predicted to be suitable swim survey areas prior to field work were actually surveyed by manta tow, along the surrounding reef slope only, as some of the reticulated linear reefs were too shallow to swim. The shelves sloping from these reefs were found to be more efficiently surveyed by tow; however, the reef structure is too dissimilar to typical backreef areas to apply the backreef accumulation density. The inability to classify these areas led to the exclusion of interior reefs of FFS from the total NWHI annual accumulation estimate. Marine surveys for derelict fishing gear have not been performed on the fringing reefs of LAY; the shallow reef area is too small to be considered significant in the annual accumulation scheme. Despite these regions in which accumulation cannot be predicted within acceptable levels of certainty, the calculated accumulation rate in Table 3 takes into account more than 85% of the predicted habitat area in the NWHI.

4.4. Hot spot maps

Along with the atoll accumulation breakdown, an analysis of the finer-scale, sub-atoll distribution of debris allows for the development of a multi-year plan to maximize the weight recovered, while still achieving adequate survey coverage across locations. The creation of density fields from observed net points reveals patterns amongst the data that are not immediately obvious with the display of simple point data. Density grids produced for KUR, MID, MAR and PHR using 2001–2005 numerical debris densities show the distribution of net 'hot spots' (Fig. 6). A visual assessment of the grids reveals a tendency for numerical densities to increase in the northern and/or eastern portions of each location. This observation tends to validate the idea that debris comes from the North Pacific convergence zone and eventually finds its way to the NWHI reef systems via the northeasterly trade winds (Brainard et al., 2000; Kubota, 1994). Although these maps do not incorporate weight and are therefore not real representations of accumulation mass, they provide a powerful visual tool to help focus future survey efforts in areas historically known to contain tight clusters of net points.

4.5. Improving accumulation prediction

This study aims to meet multiple resource management and conservation objectives. Quantifying annual debris accumulation is important for planning annual removal efforts with sufficient resources to mitigate negative impacts to the ecosystem by marine debris. For this maintenance effort to be ultimately successful there is a clear need to prioritize survey areas and focus efforts where debris accumulates at the greatest rates. Decision-making for the prioritization of survey areas must be considered first at

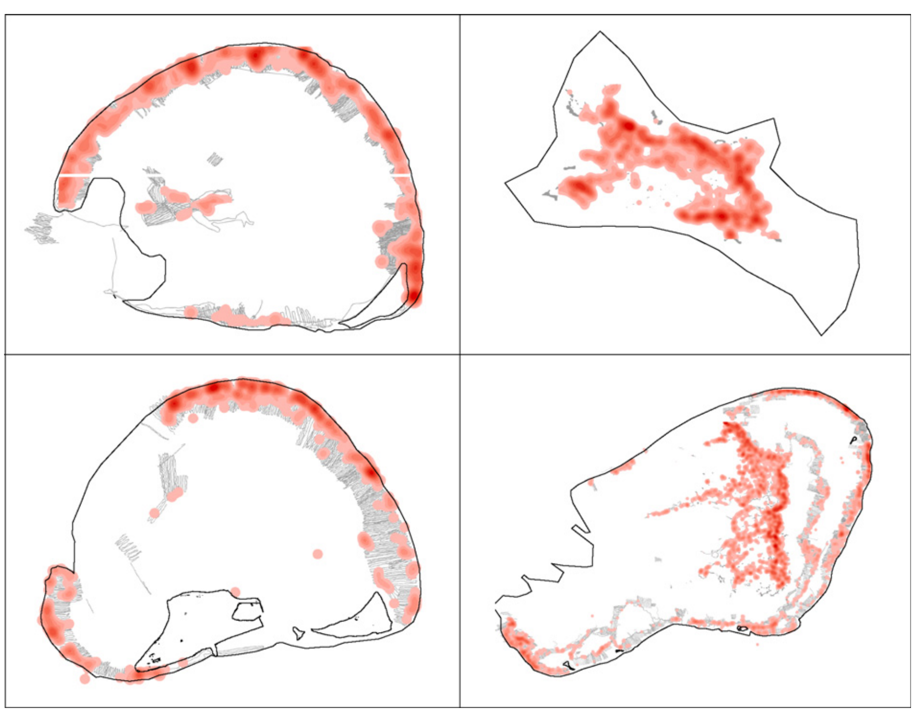

Fig. 6. Maps depicting numerical densities of debris sites marked by GPS following discovery. Dark red in the monochromatic color ramp represents the highest debris densities. Buffered survey areas are shown for each location with green lines. The locations are (clockwise from top left) Kure Atoll, Maro Reef, Pearl and Hermes Atoll, and Midway Atoll.

the atoll/reef scale and then spatially narrowed to regions within an atoll/reef.

While debris accumulation prediction using IKONOS imagery derivatives has been shown to be an effective method of incorporating depth and habitat classification, further dataset development could improve the quality of prediction. In NOAA's habitat classification scheme, some substantial areas of reef were not defined finely enough, possibly limiting the precision of the model by not allowing for elimination of habitat thought to have minimal accumulation. This was most widely seen in the outer, exposed regions of MAR and Neva Shoals and could have been a result of limited accessibility during ground-truthing procedures. The lack of habitat class precision limits the ability to filter out specific regions resulting in either the elimination of valid net habitat or the inclusion of net habitat areas where debris is unlikely to be found.

Of the three primary factors hypothesized to influence debris accumulation on the atoll/reef scale, only habitat and depth were incorporated directly. The delineation of energy regimes was considered indirectly. Consideration of the influence of large swell events and high current activity on debris settlement is limited to the use of coral community composition as a proxy for wave stress in lagoonal and backreef zones. A correlation of multi-year historical point weights to the distance from open ocean conditions could potentially be a valuable statistic for the influence of swell events on debris settlement, but individual weight data to facilitate this were not collected until 2005. Point weight data collected at PHR and KUR in 2005 show promise for this correlation (mean [lagoon] = 29.3 kg; mean (backreef) = 10.12 kg). Additionally, in data collected since 2001, the numerical-count density is more than five times greater in lagoonal areas than in backreef areas (344 and 63 nets/km^2, respectively). While the data are sufficient to infer a positive relationship between low-energy environments and heavy debris settlement, a quantitative consideration of local energy regimes would assist in distinguishing the effects of swell and current from recognized differences in effectiveness of the two survey methods.

To make sound management decisions related to marine debris, more accurate estimations of NWHI debris accumulation are needed. Estimates should consider interannual and latitudinal settlement variability, two factors that may have a significant effect on debris accumulation. The North Pacific transition zone chlorophyll front (TZCF), analogous to the STCZ, but spanning the entire subtropical Pacific west to east, shows seasonal latitudinal shift and a tendency for debris accumulation while exhibiting interannual modulations, all similar to the STCZ. The seasonal pattern of the TZCF exhibited greater-than-normal southerly migration in the El Niño years of 1998 and 2003 (Bograd et al., 2004). Based on data collected during a land-debris removal effort in the NWHI, the interannual variation is presumably less than an order-of-magnitude: 71% of yearly land debris weight totals fell within one standard deviation of the mean ($n = 7$; mean = 10,192 kg; SD = 4485 kg). Regarding the latitudinal extent of the STCZ, Polovina et al. (2001) asserted that the southerly extent of the convergence zone can reach 28° N during the winter months, the same latitude as KUR. Yet we already know that other locations in the NWHI have greater debris accumulation than KUR, showing that the described convergence zone has a wider latitudinal influence. Aerial surveys of the main Hawaiian Islands coastline in early 2006 have demonstrated that numerous masses of derelict fishing gear can reach as far south as 18° N (CRED, 2005). Through continued monitoring of debris settlement onto NWHI reefs, a broader understanding of the sources of variability associated with NWHI marine debris accumulation will be obtained, improving our capability to effectively mitigate this significant threat.

References

Bograd, S.J., Foley, D.G., Schwing, F.B., Wilson, C., Laurs, R.M., Polovina, J.J., Howell, E.A., Brainard, R.E., 2004. On the seasonal and interannual migrations of the transition zone chlorophyll front. Geophysical Research Letters 31 (L17204), 1–5.

Boland, R.C., 2006. Personal communication. In: Pacific Islands Fisheries Science Center. NOAA, Honolulu, HI.

Boland, R.C., Donohue, M.J., 2003. Marine debris accumulation in the nearshore marine habitat of the endangered Hawaiian monk seal, *Monachus schauinslandi* 1999–2001. Marine Pollution Bulletin 46, 1385–1394.

Brainard, R., 2006. Personal communication. In: Pacific Islands Fisheries Science Center. NOAA, Honolulu, HI.

Brainard, R., Foley, D., Donohue, M.J., Boland, R., 2000. Accumulation of derelict fishing gear by ocean currents threatens coral reefs of Hawaii. In: Ninth International Coral Reef Symposium, Bali, Indonesia.

Camacho-Arroyo, I., Guerra-Araiza, C., Dominguez, R., Mendoza-Rodriguez, C.A., Cruz, M.E., Cerbon, M.A., Thornton, L., Jackson, N.L., 1998. Spatial and temporal variations in debris accumulation and composition on an estuarine shoreline, Cliffwood Beach, New Jersey, USA. Marine Pollution Bulletin 36 (9), 705–711.

Convey, P., Barnes, D., Morton, A., 2002. Debris accumulation on oceanic island shores of the Scotia Arc, Antarctica. Polar Biology 25 (8), 612–617.

Coral Reef Ecosystem Division (CRED), Pacific Islands Fisheries Science Center, National Oceanic and Atmospheric Administration. 2005. Unpublished data.

Dollar, S.J., 1982. Wave stress and coral community structure in Hawaii. Coral Reefs 1 (2), 71–81.

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 confirm threat to coral reef ecosystems. Marine Pollution Bulletin 42 (12), 1301–1312.

Donohue, M.J., Brainard, R., Parke, M., Foley, D., 2002. Mitigation of environmental impacts of derelict fishing gear through debris removal and environmental monitoring. In: International Marine Debris Conference: Derelict Fishing Gear and the Ocean Environment Proceedings. Hawaiian Islands Humpback whale National Marine Sanctuary Publication, pp. 383–401.

Fernandes, L., 1990. Effect of the distribution and density of benthic target organisms on manta tow estimates of their abundance. Coral Reefs 9, 161–165.

Fernandes, L., Marsh, H., Moran, P.J., Sinclair, D.F., 1990. Bias in manta tow surveys of *Acanthaster planci*. Coral Reefs 9, 155–160.

Friedlander, A., Aeby, G., Brainard, R., Clark, A., DeMartini, E., Godwin, S., Kenyon, J., Kosaki, R., Maragos, J., Vroom, P., 2005.

The state of coral reef ecosystems of the northwestern Hawaiian islands, pp. 270–311. In: Waddell, J. (Ed.), The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2005. NOAA Technical Memorandum NOS NCCOS 11. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team, Silver Spring, MD. 522 pp.

Henderson, J.R., 2001. A pre- and post-MARPOL annex V summary of Hawaiian monk seal entanglements in the northwestern Hawaiian islands, 1982–1998. Marine Pollution Bulletin 42 (7), 584–589.

Holderied, K., Stumpf, R.P, Rohmann, S.O., Shapiro, A., Anderson, M., Smith, W., 2002. Benthic habitat mapping of Pacific Ocean coral reefs with high-resolution satellite imagery. Seventh International Conference on Remote Sensing for Marine and Coastal Environments, Miami, USA.

Hunsaker, Carolyn, T., Goodchild, M.F., Friedl, M.A., Case, T.J., 2001. Spatial Uncertainty in Ecology. Springer-Verlag, New York, p. 402.

Kenyon, J.C., Vroom, P.S., Page, K.N., Dunlap, M.J., Wilkinson, C.B., Aeby, G.S., 2006. Community structure of hermatypic corals at french frigate shoals, northwestern Hawaiian islands: capacity for resistance and resilience to selective stressors. Pacific Science 60 (2), 153–175.

Kenyon, J.C., Aeby, G.S., Brainard, R.E., Chojnacki, J.D., Dunlap, M.J., Wilkinson, C.B., 2006. Mass coral bleaching on high-latitude reefs in the Hawaiian archipelago. In: Proceedings of the Tenth International Coral Reef Symposium, Okinawa 2, pp. 631–634.

Kubota, M., 1994. A mechanism for the accumulation of floating marine debris north of Hawaii. Journal of Physical Oceanography 24 (5), 1059–1064.

Moran, P.J., De'ath, G., 1992. Suitability of the manta tow technique for estimating relative and absolute abundances of crown of thorns starfish (*Acanthaster planci* L.) and corals. Australian Journal Marine Freshwater Research 43, 357–378.

National Oceanic and Atmospheric Administration (NOAA), 2003. Atlas of the Shallow-Water Benthic Habitats of the Northwestern Hawaiian Islands, pp. 160.

Pichel, W.G., Veenstra, T., Churnside, J., Arabini, E., Friedman, K.S., Foley, D., Brainard, R., Kiefer, D. Ogle, S., Clemente-Colon, P., 2003. Ghost net-derelict net detection in the North Pacific and Alaska waters using satellite and airborne remote sensing and surface drifters. In: Thirtieth International Symposium on Remote Sensing of the Environment, Honolulu, USA.

Polovina, J.J., Howell, E., Kobayashi, D.R., Seki, M.P., 2001. The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. Progress in Oceanography 49, 469–483.

Slip, D.J., Burton IV, H.R., 1991. Accumulation of fishing debris, plastic litter, and other artefacts, on Heard and Macquarie islands in the Southern Ocean. Environmental Conservation 18 (3), 249–254.

Storlazzi, C.D., Field, M.E., Dykes, J.D., Jokiel, P.L., Brown, E., 2001. Wave control on reef morphology and coral distribution: Moloka'i, Hawai'i. In: WAVES 2001 Conference Proceedings, American Society of Civil Engineers, San Francisco, California, 1, pp. 784–793.

Stumpf, R.P., Holderied, K., Sinclair, M., 2002. Mapping coral reef bathymetry with high-resolution, multispectral satellite imagery. In: Seventh International Conference on Remote Sensing for Marine and Coastal Environments, Miami, USA.

Veenstra, T.S., Churnside, J.H., Pichel, W.G., Foley, D., 2004. High seas driftnet detection in the North Pacific using remote sensing technologies. In: AGU Twelfth Ocean Sciences Meeting, Portland, Oregon.