DYNAMICS OF DEBRIS DENSITIES AND REMOVAL AT THE NORTHWESTERN HAWAIIAN ISLANDS CORAL REEFS

BY

RAYMOND BOLAND[1], BRIAN ZGLICZYNSKI[1], JACOB ASHER[2], AMY HALL[2], KYLE HOGREFE[2], and MOLLY TIMMERS[2]

ABSTRACT

Previous marine debris studies in the Northwestern Hawaiian Islands (NWHI) have focused on the density, type, and tonnage of debris in various reef and island habitats. Cleanup efforts have grown from a single ship working for a small amount of time to multiple vessels for extended periods. A key element to determining the effectiveness of these efforts is the decline of debris density relative to accumulation rate in these habitats. Study sites were monitored and cleaned for up to 5 years from 1999 to 2003. We measured densities, estimated accumulation rates and projected the number of days required to completely clean the atolls. Initial clean-up efforts (1999) at two atolls removed 28-63 debris items per km^2 with a total cleanup of the atolls estimated to require 45 years. In subsequent years, improved techniques and greater effort has resulted in an overall pattern of decreasing debris densities, projected debris levels and projected workdays to completely clean the atolls. In the final year (2003), densities at the same two atolls ranged from 6-12 debris items per km^2 with cleanup estimated to require 13 years. This pattern suggests the rates of debris removal within the study sites have surpassed the rate of debris accumulation and removal activities are effectively reducing debris levels. To effectively deplete the debris below current levels, an effort should be made to decrease accumulation rates by intercepting debris at sea and preventing loss and discarding of fishing gear.

INTRODUCTION

Marine debris is one of the largest documented anthropogenic impacts in the Northwestern Hawaiian Islands (NWHI). The Pacific Islands Fisheries Science Center Marine Debris Program began in 1996 in response to the growing threat of entanglement of the endangered Hawaiian monk seal, *Monachus schauinslandi,* in derelict fishing gear (Henderson, 2001). Removal of the derelict fishing gear began with a single vessel manned by a few divers for a few weeks per year and has expanded to an extensive program with many divers working up to 5 months each year. Currently, 440 metric tons of debris has been removed from the NWHI habitats.

[1]NOAA Pacific Islands Fisheries Science Center, 2570 Dole Street, Honolulu, HI 96822 USA,
E-mail: Raymond.Boland@noaa.gov
[2]Joint Institute for Marine and Atmospheric Research and NOAA Pacific Islands Fisheries Science Center, 1125B Ala Moana Blvd., Honolulu, HI 96814 USA

Gerrodette (1985) theorized that marine debris could be modeled as a dynamic population that moved with wind and water masses and that debris density would be a function of these physical variables. Using debris densities as an index of total debris level, we used area-specific accumulation rates and debris cleanup data to extrapolate the amount of effort required to completely clean the atolls. We define a successful cleanup as the complete removal of all debris items to a density of zero. For this to occur, the removal rate of debris must exceed the rate at which ocean currents deposit debris at the atoll.

METHODS

Study Sites

Nearshore study sites were established (Donohue et. al., 2001a) at three NWHI atolls: Pearl and Hermes Atoll (PHA) and Lisianski Island (LIS) in 1999, and Kure Atoll (KUR) in 2000. Study site areas ranged between 1.0 and 1.3 km^2 and were 0.5 to 10.0 meters deep. Each study site was located on the northeast side of the reef complex, between an island and the seaward barrier reef, and was directly exposed to trade winds.

Survey Procedures and Estimation of Debris Density

Study sites were surveyed annually from 1999 to 2003 to identify debris, monitor debris densities, and remove all debris found. Support vessels ranged from 30 to 70 meters in length and conducted operations on site from 20 to 120 days. In all cases small craft were dispatched from the support vessels to conduct the survey and removal of submerged derelict fishing gear within the study site. All debris items in this study were large enough to be an entanglement hazard to marine life and consisted primarily of lost and discarded fishing gear such as nets and line.

Typically four craft, each with a crew of four, would work the survey site with two craft surveying and two craft removing. Debris encountered by the survey divers was marked with a Global Positioning System (GPS) point. This information was passed to the removal craft following the survey team. From the survey craft two snorkel divers were towed approximately 10 m behind a small boat at a speed of 1 to 2 knots. Divers visually surveyed the water column using strip transects approximating a parallel track search pattern (Ribic et al., 1992). During towed surveys, divers held plywood boards (90 cm x 30 cm x 2 cm) to steer themselves in an oscillating pattern from the surface to depth while serpentining from side to side.

Surveys were conducted only when divers could see the bottom clearly from the water surface, and thus we assumed a uniform vertical detection probability. The effective swath width of transects was determined according to measured water clarity. Water clarity was visually estimated at the outset and conclusion of each transect. Visibility estimates were obtained by stationing one diver in the water and instructing the second diver to swim away from the first diver holding a piece of green trawl net of less than 5 m^2 in area, suspended approximately 1 m below the surface of the water. When the net was no longer visible to the first diver, the distance of the net from the sighting diver was recorded as the visibility estimate. For each transect, the potential visible swath width was estimated at two times the mean of the initial and final water visibility estimates. The effective swath width utilized was the lesser of the potential visible swath width or 15 m, the maximum width in which we expected divers to be able to uniformly detect debris present. We assumed a uniform detection probability within the effective sampling swath. Tracks of survey transects were logged with GPS units (Garmin 12 and 76, Garmin International) and downloaded to Geographic Information System (GIS) software (ARCVIEW, ESRI Inc.) daily. The area surveyed was estimated as the product of the transect length and swath width. Debris density (debris items/ km^2) was estimated by dividing the total number of debris items encountered by the size of the area surveyed.

Debris Accumulation

A GIS overlay procedure was used to compare the initial survey transects to survey transects completed the following year. The area of overlap between initial and subsequent surveys was defined as the area resurveyed. The same process was followed for consecutive years at each of the three study sites. All debris found in the resurveyed area was assumed to have accumulated since the previous year's survey and was used to estimate the annual accumulation (Boland and Donohue, 2003).

Projection of Time Required to Completely Clean the Atolls

The effort required to completely clean an atoll was defined in workdays. A workday consisted of a small craft with a crew of four either surveying or removing debris for a period of 8 hours. The eight-hour time period included transit to and from the support vessel to the study site, and all time spent surveying and removing debris.

Projections of the amount of time required to completely clean each of the atolls were made in three steps. First, the area cleaned per workday at each atoll was determined by dividing the total area cleaned within the atoll's study site by the number of workdays at the study site. Then, within each atoll, an estimate of the total area with habitat similar to the study site was determined using maps of shallow-water benthic habitat[1]. Area estimates used for this study included habitat 10m or shallower. Many areas are too deep or lack complex hard bottom that collects marine debris; such areas were excluded from the total estimated area. Types of habitat excluded included areas specified by the atlas to be deep water (>20 meters), unconsolidated sediment, and undescribed areas. Finally, estimates of the amount of time required to completely clean each of the atolls were derived by dividing the total habitat area by the area cleaned per workday.

The total weight of each boatload of debris removed was determined using a scale attached to the vessels' cranes. Cumulative weights were pooled with the weight of debris found on the beach at each of the atolls. These values were then divided by the number of workdays at the site to compute the average mass of debris removed per workday.

RESULTS

Overall, the area surveyed at the three study sites increased over the 5 years of effort (Table 1). Debris density (Fig. 1), accumulation (Fig. 2) and the number of debris items (Table 2) within the survey sites decreased during the 5 years of monitoring. KUR had 4 times the accumulation rate of PHA and LIS. Projections of debris levels for the southern atolls (PHA, LIS) increased during the early years and then precipitously declined, whereas projections for the northernmost atoll (KUR) declined every year except 2003 (Fig. 3). Overall, the projection of workdays needed to clean up the atolls declined (Fig. 4). The number of workdays required to clean LIS started much higher than for PHA and then declined to a level consistent with PHA and KUR. Finally, the mass of debris harvested per workday rose dramatically between 2001 and 2002, then declined slightly in 2003 (Fig. 5).

DISCUSSION

Towboarding is an effective method for surveying benthic targets (Fernandes, 1990; Fernandes et al*.,* 1990; Moran and De'ath, 1992). Fernandes (1990) tested differences in the sightability of small targets (40 cm diameter) using different survey widths. A survey width of 9 to 15 meters, consistent with our methods, had the highest correlation of sighted targets vs. true targets. Presently there are no estimates of sighting error. However, nearly all pieces of marine debris encountered in this study were relatively large targets (> 40 cm) that tended to float up from the seafloor, making them conspicuous and difficult to miss.

At PHA, debris density increased and then decreased while density at the other two atolls did not. This is due to a difference in the accumulation between the first half and the second half of the study. The accumulation rate during 2000-2001 was nearly twice the rate for 2002-2003. Debris density and accumulation at KUR decreased except in 2003, when a rise in accumulation increased density.

Debris density and accumulation conformed to a latitudinal trend. These variables were low at the two southernmost atolls, PHA and LIS, with the lowest densities and accumulation at LIS.

Accumulation of debris may be affected by the Subtropical Convergence Frontal Zone (STCFZ). The STCFZ is defined by both a thermohaline front and atmospheric forcing by the North Pacific Ocean subtropical high (Roden, 1991), which create a convergence of oceanic surface waters north of the NWHI from latitude 31º N to 34º N (Roden, 1991). The frontal zone has been proposed as a mechanism for transporting a disproportionately large amount of debris to the northern-most locations in the Hawaiian Islands (Ingraham and Ebbesneyer, 2001; Donohue et al*.,* 2001a, b). This mechanism

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

is supported by our reported accumulation patterns at the three study sites. Kure Atoll, the northernmost study site and closest to the STCFZ, consistently had the highest accumulation, whereas LIS, the southernmost study site and furthest from the STCFZ, consistently had the lowest accumulation.

The number of projected debris items was influenced by both debris density and atoll size. Because PHA had a higher density than LIS, it had a larger projected number of debris items despite being 30 percent smaller. Because KUR is smaller than PHA, clean-up efforts reduced the density quickly at KUR, leaving PHA with the highest projected debris levels in 2001 and 2002.

Differences in the projected number of workdays were affected primarily by the total area of habitat at each atoll rather than debris density. Projected workdays decreased over time at LIS and PHA but remained higher than those for KUR. Because of its larger size, LIS required four times the number of workdays needed for PHA and KUR. It is possible that the smaller area surveyed at LIS in 1999-2001 affected the precision of the estimate, and in fact the LIS projections for the first 3 years of monitoring may have a positive bias. The high density value for LIS in 1999 (Fig. 1) may indicate the reduced precision associated with smaller survey areas. Because of its smaller size, KUR had a lower and relatively constant number of projected workdays even though it had the highest density and accumulation.

The density of debris found and removed was greater than accumulation at all sites except for KUR. Current removal efforts at PHA and LIS have effectively reduced debris levels so low that this type of survey and removal is exhibiting diminishing returns. In 2001, 8 workdays were spent surveying 57% of the study site at PHA and recorded the highest debris density and accumulation. In 2003, 6 workdays covered 96% of the area but debris density and accumulation were at their lowest. KUR has a much higher accumulation rate and current removal efforts have been insufficient there.

The rate of accumulation is an important consideration for estimating debris density, projected debris levels, and projected workdays. The focus for further work should be to decrease accumulation. Extensive effort is required to send small craft into the shallows and use divers to remove debris by hand. One way to improve the efficiency of removal efforts would be to decrease accumulation by intercepting the debris before it reaches the atoll habitats. Satellites and airborne remote sensing have been used successfully to locate debris in Alaskan waters. Once debris was located on the high seas, a ship could intercept it and haul it aboard with deck cranes. Another possibility would be a program to pay fisherman to retrieve debris they encounter on the high seas. The ideal strategy would be both a removal effort on the high seas using remote sensing and the continued removal of debris in the atoll habitats by divers.

Because our accumulation estimates, projected debris levels, and projected workdays are based on extrapolating from a single study site at each atoll, they must be regarded with caution. Atoll habitats with differing degrees of relief will snag and retain variable amounts of passing debris. Measurements of accumulation and debris densities linked to specific habitats are needed to better reflect spatial variability in debris densities and produce more comprehensive and reliable estimates of overall debris levels and the effort required to clean the atolls. It may be possible to determine debris accumulation and densities within various habitats using the recently drafted benthic habitat maps for the NWHI. Using the habitat atlas, a pilot effort focused on a new study site of complex, reticulated shallow reefs in the center of Pearl and Hermes Atoll and produced a preliminary annual accumulation estimate of 158 items/km^2, an estimated total debris level of 84,096 items, and a projection of 83,677 workdays to clean the reef (Jacob Asher, Joint Institute of Marine and Atmospheric Research, University of Hawaii, unpublished data). These values are far higher than those determined from our study site. The differences in these estimates illustrate the difficulties and remaining uncertainties in assessing the magnitude of marine debris.

The current success at finding and removing debris at KUR, PHA, and LIS is trending downward. At LIS and PHA, removal clearly exceeds accumulation, resulting in declining estimates of debris density and projected workdays. At these locations current marine debris survey and removal operations appear to be at a point of diminishing returns. Alternate techniques should be explored to reduce accumulation.

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Table 1. Area of the three study sites surveyed by site and year.

		Percent surveyed				
Atoll	Study site (km^2)	1999	2000	2001	2002	2003
LIS	1.17	38[a]	27[a]	33[a]	60	58
PHA	1.00	66[a]	64[a]	57[a]	92	96
KUR	1.26	NA	69[a]	61[a]	75	57

[a] From Boland and Donohue (2003).

Table 2. Atoll area 10 meters and shallower (Area), debris items on survey transect not in resurveyed area (O), debris items in resurveyed area (A) and total debris items surveyed (T).

		Debris items outside of resurveyed area, in resurveyed area and total debris surveyed in study site.														
Atoll	Area	1999			2000			2001			2002			2003		
		O	A	T	O	A	T	O	A	T	O	A	T	O	A	T
LIS	363.2	28	NA	28	6	2	8	11	0	11	3	1	4	4	0	4
PHA	244.6	18	NA	18	52	14	66	30	12	42	12	6	18	3	9	11
KUR	69.9	NA	NA	NA	144	NA	144	33	60	93	17	27	44	10	40	50

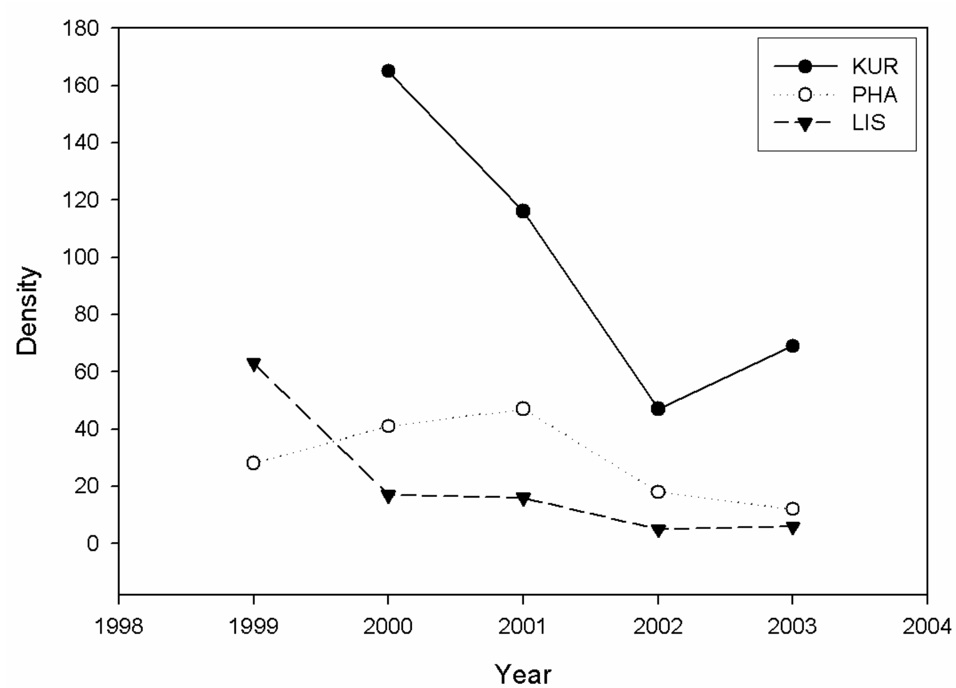

Figure 1. Debris density (debris items/km^2) by year at the three study sites: Lisianski Island (LIS), Pearl and Hermes Atoll (PHA) and Kure Atoll (KUR). All items identified in the survey were removed. Data for 1999 are from Donohue et al. (2001a).and those for 2000-2001 from Boland and Donohue (2003).

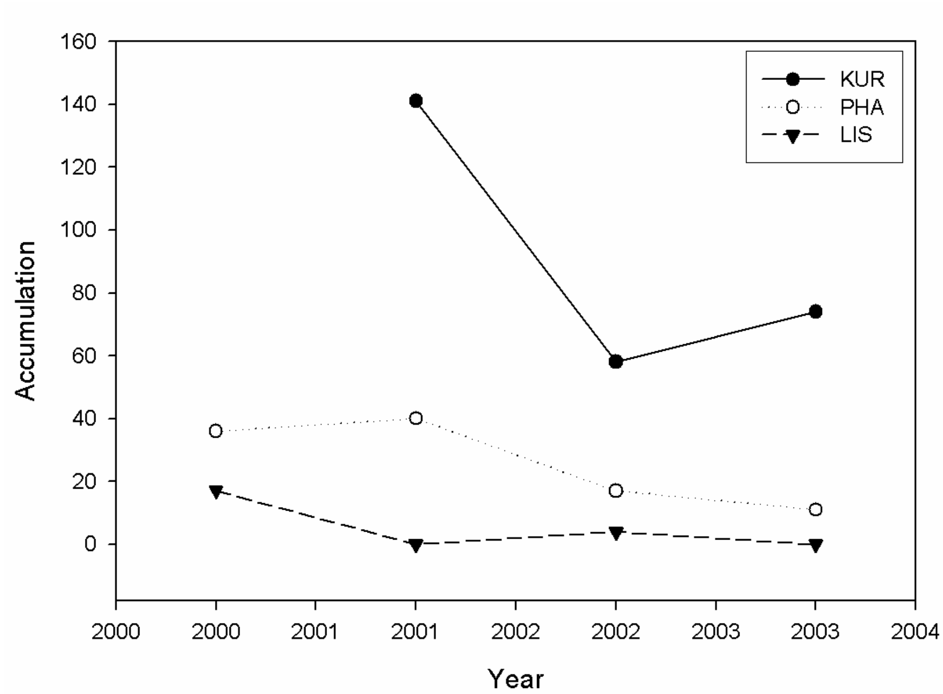

Figure. 2. Annual debris accumulation (debris items/km^2) at the three study sites: Lisianski Island (LIS), Pearl and Hermes Atoll (PHA) and Kure Atoll (KUR) . Data for 2000-2001 are from Boland and Donohue (2003).

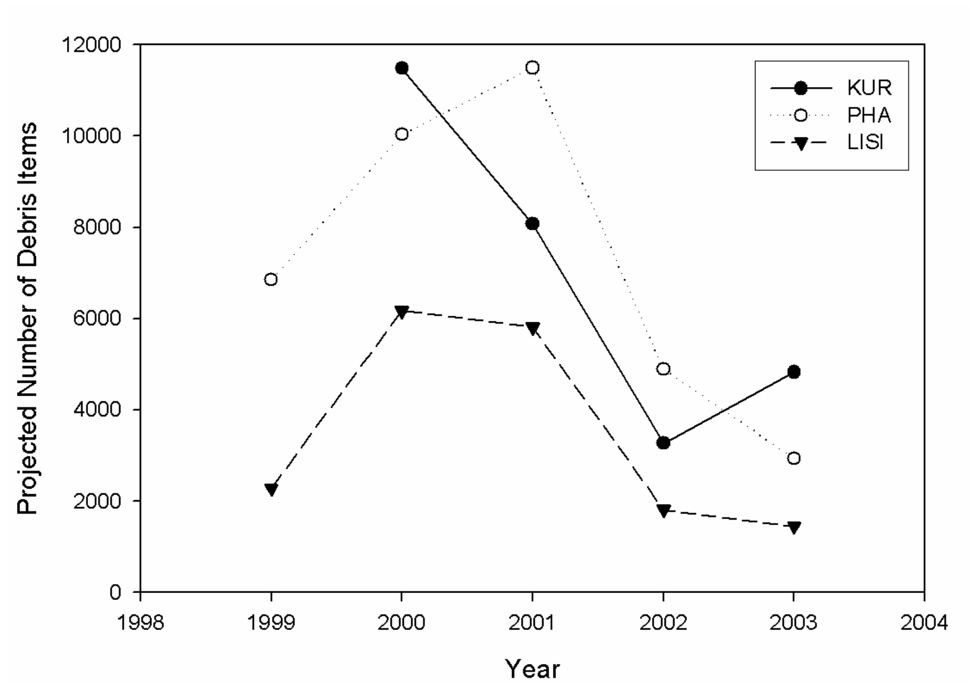

Figure. 3. Annual projections of total debris levels for the entire area (10-meter isobath and shallower) at the three study sites: Lisianski Island (LIS), Pearl and Hermes Atoll (PHA) and Kure Atoll (KUR).

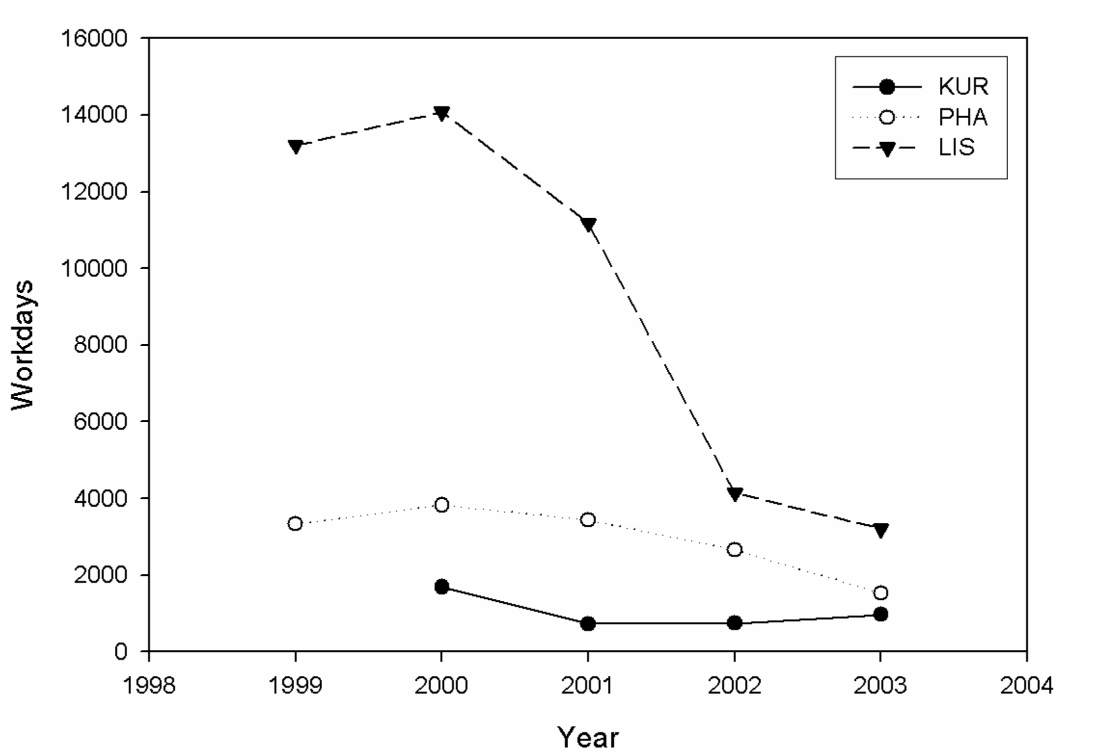

Figure 4. Annual projections of the number of workdays required to completely survey and remove all debris within atolls (10-meter isobath and shallower) at the three study sites: Lisianski Island (LIS), Pearl and Hermes Atoll (PHA) and Kure Atoll (KUR).

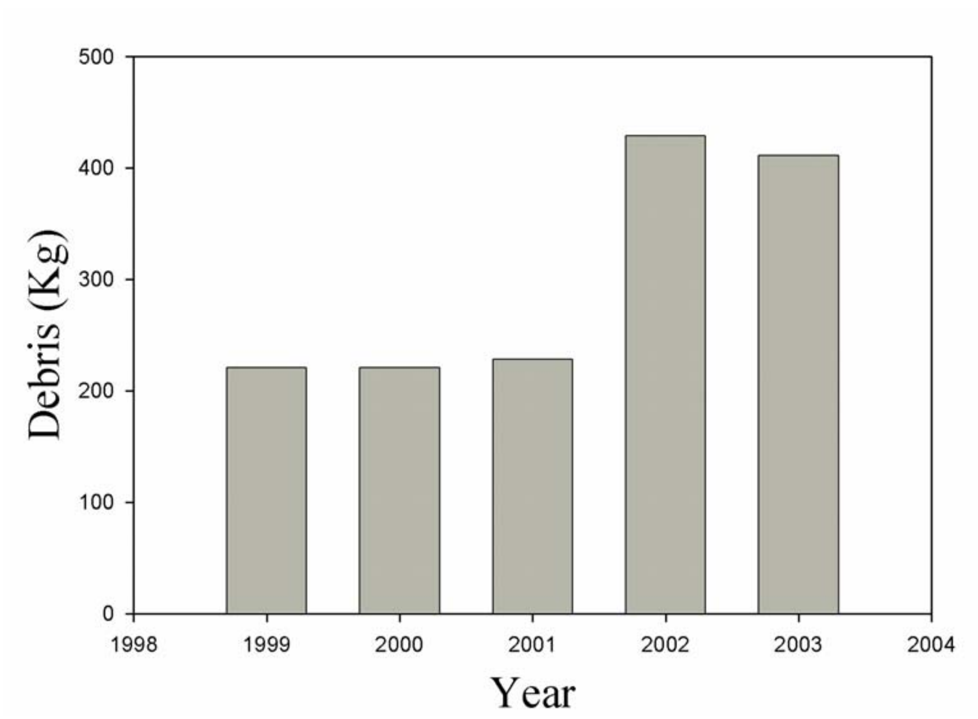

Figure 5. Annual estimates of the total weight (kg) of debris removed per workday from the water and beaches at all three atolls combined

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