Title: Removing plastic benefits marine ecosystems: evidence from four decades of endangered seal entanglement

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Abstract: Abandoned, lost, or otherwise discarded fishing gear causes tremendous harm to marine species and ecosystems. To mitigate the destruction wrought by these ocean plastics, various cleanup programs have been established, though benefits of such efforts to marine species and ecosystems have not been demonstrated. We examined over 40 years of Hawaiian monk seal marine debris entanglement records before and after large-scale marine debris removal efforts were initiated in the Northwestern Hawaiian Islands, demonstrating a significant reduction in entanglement rate where debris removal effort was most concentrated. Large-scale and sustained removal of abandoned, lost, or otherwise discarded fishing gear meaningfully benefits marine ecosystems and has the potential to be transformational in restoration efforts.

One-Sentence Summary: Large-scale removal of plastic restores marine ecosystems evidenced by reduced entanglement of endangered Hawaiian monk seals.

Main Text: Plastic pollution is a documented threat and increasing menace to marine ecosystems worldwide (*1—3*). Plastics replaced biodegradable fishing gear materials in the early 1970s and plastic fishing gear is ubiquitous today (*4—6*). Derelict fishing gear is a particularly destructive component of total plastic marine debris as fishing gear is expressly designed to capture and kill marine life, a function it relentlessly performs after it has been abandoned, lost, or otherwise discarded (*4*). Estimates of fishing gear loss provide some understanding of the scale of this problem, though definitive knowledge of the total amount of abandoned, lost, or otherwise discarded fishing gear generated worldwide is unknown. Annual routine loss of fishing gear has been estimated to be from two to thirty percent worldwide (*7, 8*). Industrial trawl, purse-seine, and pelagic longline fisheries are estimated to lose a median of 48.4 kt (95% confidence interval, 28.4 to 99.5 kt) of gear yearly during normal fishing operations (*9*). This estimate excludes abandoned or discarded gear and derelict gear such as driftnets/gillnets, pots and traps, and gear from nearshore and small-scale fisheries. The contribution of illegal, unreported and unregulated fishing to abandoned, lost, or otherwise discarded fishing gear is unknown (*1*).

Though they include some data from the Pacific Ocean, comprehensive studies on fishing gear loss have largely focused on vessel and gear types and fishing techniques rather than geographic analyses at the ocean basin scale (7—9). More is known about fishing gear loss in the Pacific once it has become ocean plastic pollution. For example, in the infamous plastic accumulation zone known as the North Pacific Garbage Patch 75 to 86% of all floating plastic larger than 5 cm has been attributed to derelict fishing gear (nets, lines, hard plastic buoys and boxes, etc.) and a minimum of 46% of North Pacific Garbage Patch debris by mass was estimated to be ghost gear and nets (*10—12*).

To mitigate the destruction wrought by marine plastics, various efforts have been established to remove harmful plastic debris including abandoned, lost, or otherwise discarded fishing gear (*13—16*). However, to date, evaluation of the efficacy of cleanup programs, especially regarding definitive benefits to marine species and ecosystems, has been lacking. Here, we quantitatively demonstrate for the first time that large-scale and sustained removal of derelict fishing gear meaningfully benefits marine ecosystems and has the potential to be transformational in restoration efforts.

The Northwestern Hawaiian Islands are a remote, isolated, and largely uninhabited part of the Hawaiian Archipelago, often mischaracterized as “pristine” (*17*) (Fig. 1). United States President Theodore Roosevelt created the first protections for these islands in 1903; further measures were added over time, culminating in 1.5 million square km now designated as the Papahānaumokuākea Marine National Monument. Monument status confers various protections such as access by permit only and prohibition of commercial fishing. Despite these measures, the Northwestern Hawaiian Islands are not at all pristine. Ocean currents concentrate marine debris from throughout the North Pacific in a subtropical convergence zone inundating these islands with huge quantities of plastic waste from distant sources (*18—20*). A conservative estimate indicates over 50 mt of abandoned, lost, or otherwise discarded fishing gear accumulates in the Northwestern Hawaiian Islands annually (*14*). Approximately 100 mt are now being removed every year during dedicated expeditions. The annual rate of removal of this ocean plastic pollution could be higher, but is limited by funding and logistical constraints. The Northwestern Hawaiian Islands provide an informative model for evaluating the efficacy of marine debris removal and associated putative ecosystem and conservation benefits.

Impacts of marine plastics on Northwestern Hawaiian Island ecosystems have been documented for decades (*13,15, 21—23*). Entanglement in marine plastics, primarily derelict fishing gear, has been identified as a major threat to the persistence of the endangered Hawaiian monk seal (*Neomonachus schauinslandi*), one the rarest pinnipeds in the world with just 1,600 surviving individuals (*24, 25*). The U.S. Endangered Species Act and Marine Mammal Protection Act require mitigating threats to the Hawaiian monk seal. Consequently, disentangling seals from plastic debris and removing potentially entangling debris from beaches and nearshore waters where seals are found have been high priorities of the U.S. National Oceanic and Atmospheric Administration since the early 1980s (*21*).

From 1996-1998, the U.S. National Oceanic and Atmospheric Administration explored methods for in-water detection and removal of abandoned, lost, or otherwise discarded fishing gear from coral reefs within the monk seal's primary habitat. In 1999, systematic survey and industrial-scale removal of in-water marine debris, coupled with quantitative analyses, were initiated in the Northwestern Hawaiian Islands (*13*). These efforts involved one or more large sea-going vessels, a fleet of small open boats, and teams of divers (*13*). This work grew into the world's largest in-water marine debris mitigation effort in terms of area remediated and mass of derelict fishing gear removed and continues today (23, 26).

Hawaiian monk seal entanglement is a conspicuous and measurable negative impact of abandoned, lost, or otherwise discarded fishing gear that we propose can also serve as a broader signal of harm inflicted on Northwestern Hawaiian Island ecosystems by ocean plastics. For example, insight on the exposure of other marine taxa to plastic entanglement and ingestion may be gleaned from seal entanglement rates. We analyzed a unique, long-term data set of more than 40 years of documented Hawaiian monk seal entanglement incidents, detailed Hawaiian monk seal monitoring data, and spatial and temporal data on plastic debris removal to show entanglement hazards were successfully reduced following the initiation of large-scale marine debris removal. We further propose that these data provide a heretofore absent metric for the benefits of large-scale plastic debris removal in ecosystem remediation and restoration.

Hawaiian monk seal entanglement rates

Hawaiian monk seals have been the subject of monitoring, research, and active conservation efforts since the early 1980s. The species is distributed in a metapopulation and seasonal surveys are conducted annually at six monk seal subpopulations which occur at French Frigate Shoals, Laysan Island, Lisianski Island, Pearl and Hermes Reef, and Midway and Kure Atolls (Fig. 1). Additional monk seal subpopulations not included in this study occur at Necker and Nihoa Islands and in the main Hawaiian Islands. Seal demographic information is largely obtained by marking each new annual cohort of weaned pups and resighting known individuals throughout their lives during regular surveys of all shoreline areas where seals land to rest, give birth, and nurse their pups (*27*).

A total of 437 monk seal entanglements involving animals of both sexes and a wide range of ages were documented in the Northwestern Hawaiian Islands from 1974[1] to 2022. Plastic derelict fishing gear (net, line, and trap components) accounted for 76% of the items observed entangling seals. Only one non-plastic entangling item (a loop of copper wire) was observed. Documented

[1] A few incidents were recorded opportunistically prior to the establishment of the monitoring program in the 1980s.

incidents represent only a subset of the actual number of seal entanglements because entangled seals are not always observable, and when they are, they are not always detected. Seals alternate time at sea with periods ashore, but are practically only available for detection of entanglement when on land. For example, seals entangled in debris anchored to offshore substrate or in debris too large to swim to shore with are essentially unavailable for detection and almost certainly perish unseen and undocumented. Further, field staff are only present for part of the year at most sites where monk seals reside; when observers are absent, the entanglement detection probability is zero.

The aforementioned availability and detectability issues, coupled with uncertainty regarding the number of individuals in seal subpopulations exposed to plastic pollution, have bedeviled efforts to obtain consistent quantitative entanglement rates that are comparable over space and time. We therefore developed a novel entanglement rate metric that uses monk seal monitoring data collected using standardized protocols at all Hawaiian monk seal subpopulation locations over several decades (*27*). To eliminate uncertainty associated with abundance, minimize variability in detection availability, and maximize probability of detection and sample size, we based our entanglement rate on a single demographic group, weaned pups. The rate is calculated as the number of weaned pup entanglements observed during periods of standardized data collection divided by the number of observed weaned pup exposure days. Observed weaned pup exposure days are calculated as the sum of days when each weaned pup was exposed to entanglement hazards during periods of standardized data collection. This entanglement rate metric was calculated for six subpopulations; French Frigate Shoals, Laysan Island, Lisianski Island, Pearl and Hermes Reef, Midway Atoll, and Kure Atoll. At Midway Atoll, observation effort could not be quantified as it was elsewhere; consequently, the entanglement rate metric accounted for the number of weaned pup exposure days but not for observation effort. This likely resulted in negatively-biased entanglement rates at Midway Atoll.

Debris removal

From 1996 to 2022, a total of 945 mt of marine debris, primarily abandoned, lost, or otherwise discarded fishing gear, were removed from six monk seal subpopulation sites in the Northwestern Hawaiian Islands (Fig. 2). The quantity of debris extracted varied considerably among locations (Fig. 3). By far, the largest amount (505 mt) of debris was removed from Pearl and Hermes Reef.

We fitted Poisson regression models to test whether weaned pup entanglement rates differed before and after large-scale marine debris removal which began in 1999 (*27*). We also evaluated models that included potentially influential factors including subpopulation and year. The two best-fitting models (with Akaike Information Criterion differing by 1.3) both included subpopulation and time period; one model with additive effects and the other with an interaction (Table S1). These results indicate that entanglement rates differed among subpopulations and were lower after debris removal began, but that the removal effect may have varied in magnitude with subpopulation (Table S1). Prior to the debris removal efforts, entanglement rates were relatively greater at the more northerly seal subpopulation sites, Lisianski Island, Pearl and Hermes Reef, and Kure Atoll, as compared to Laysan Island and French Frigate Shoals to the southeast (Fig. 4). Midway Atoll entanglement rates were relatively low, but as noted above are likely negatively biased. Further examination of the debris removal effect at each subpopulation showed that entanglement rates fell at five of the six seal subpopulation sites. This change was statistically significant at Pearl and Hermes Reef (Table S2) where 1) the entanglement rate declined by 71% following debris removal, and 2) the total amount of debris removed was from 2.5 to more than 13-fold greater than at the other subpopulation sites where statistically significant effects were not detected.

Discussion

Our results demonstrate for the first time that a sufficiently intensive and sustained marine debris removal program, such as that pursued at Pearl and Hermes Reef, can effectively reduce wildlife entanglement hazards. This program may serve as a proxy for the mitigation of ocean plastics at the ecosystem level. We postulate that the statistically significant result obtained for Pearl and Hermes Reef was due to three circumstances. First, this subpopulation had a relatively high "baseline" entanglement rate prior to debris extraction efforts. Second, the amount of debris removed from Pearl and Hermes Reef was vastly higher than any other location. Lastly, the rate of debris removal was very high in the early years of the debris cleanup program, resulting in more numerous subsequent years when entanglement hazards were reduced as compared to other sites where debris removals accrued more gradually.

Our finding that the effect of debris removal on monk seal entanglement rates varied among subpopulations likely reflects known and unknown variability in debris exposure risk among sites. Entanglement risk likely depends upon the absolute amount as well as the distribution of debris in habitats used by weaned pups. The degree to which debris removal reduces that risk presumably depends on the amount of legacy debris present when removal efforts began, the debris accumulation rate, the amount of debris removed, and the timing of those removals. We only have robust site-specific information on the latter two factors, the timing and amount of marine debris removed, although studies suggest islands and atolls situated furthest north and closest to the subtropical convergence zone receive the greatest amount of debris (*14, 16*). This is corroborated by the distinctly higher entanglement rates observed at Kure Atoll, Pearl and Hermes Reef, and Lisianski Island prior to debris removal.

Lisianski Island had the highest entanglement rates both before and after debris removal. This island is located adjacent to Neva Shoals, an extensive coral reef area far larger than that associated with any of the other monk seal subpopulation sites. As Neva Shoals is not an atoll, it lacks a barrier reef and lagoon, features which are believed to enhance deposition and retention of large quantities of derelict fishing gear (*14*). Two studies (*13, 15*) found that debris densities and accumulation rates in waters surrounding Lisianski Island were relatively lower than at other Northwestern Hawaiian Islands sites. Conversely, they found that debris accumulation on beaches at Lisianski Island was far higher than elsewhere, indicating that derelict fishing gear tends to be driven across reef areas and deposited on the island. This may result in elevated entanglement risk, especially for naïve weaned pups that are just beginning to investigate the littoral and nearshore marine environments.

Though not statistically significant, reduced rates of entanglement at Lisianski Island, Midway Atoll, and Kure Atoll indicate that debris removal efforts benefitted seals there as well. Lastly, entanglement rates at both Laysan Island and French Frigate Shoals were already relatively low before debris removal began, leaving little room for detection of statistically significant improvement.

Reduced monk seal entanglement is undoubtedly a proxy for many undocumented benefits to other Northwestern Hawaiian Island species as well as ecosystem function, health, and resilience. The fact that we were able to detect a signal in seals surely suggests that plastic debris impacts to many other reef-associated species have also eased. During just one expedition to Pearl and Hermes Reef in 1999, 23 species including bony fish, crabs, shrimp, lobster, sea stars, and marine worms were documented entangled in or within derelict fishing gear, confirming impacts across taxa and trophic levels (*13*). Marine turtle entanglement in derelict fishing gear may restrict their movement and result in wounding and death (*28, 29,* Fig. 2D). Seabirds become entangled in debris both on shore and at sea and some are known to incorporate debris as nesting material with associated adult and nestling mortality (*30*). Impacts to corals from derelict fishing gear are known to include tissue damage, breakage, susceptibility to infection and algal overgrowth, and polyp and colony mortality (*31—35*). Coral reefs in the Northwestern Hawaiian Islands damaged by abandoned, lost, or otherwise discarded fishing gear show significant changes to benthic functional groups with significantly more bare substrate and less living coral and algal cover (*23, 36*). These disturbed reef areas are slow to recover after debris removal and exhibit changes to benthic community structure and composition (*36*). Ocean plastic debris is known to have wide-ranging negative ecological impacts beyond entanglement, including habitat degradation, trophic transfer of plastics and associated toxins, a vector for invasive species, and the reduction of ecosystem services (*1, 4, 23, 36—38*). Consequently, removal of ocean plastics from the Northwestern Hawaiian Islands benefits marine ecosystems through reduced harm and impacts to a broad range of taxa. Our findings suggest that if the level of debris removal achieved at Pearl and Hermes Reef were attained at subpopulations where monk seal entanglement rates remain relatively high, benefits to monk seals and the ecosystem at-large could be maximized. Moreover, although entanglement rates of monk seals at Laysan Island and French Frigate Shoals are relatively low, many other species at those sites would benefit from continued and expanded cleaning of the reefs.

We have shown that sufficiently ambitious and sustained removal of marine debris, particularly abandoned, lost, or otherwise discarded fishing gear, can achieve intended conservation benefits. This approach is therefore viable and urgently needed but we emphasize that reducing environmental plastic inputs is vastly preferrable to only mitigating their damage after-the-fact. The entangling plastic debris aggregated in nearshore waters and ultimately deposited on Hawaiian reefs and beaches largely originates from multi-national regulated, as well as illegal, unreported and unregulated fisheries throughout the Pacific. Consequently, efforts to reduce these inputs from legal international fisheries are needed. Given the illegitimate nature of illegal, unreported and unregulated fishing and its escalation (*39, 40*), addressing such fishing in the context of abandoned, lost, or otherwise discarded fishing gear is also warranted. Efforts to reduce inputs from fisheries coupled with ambitious removal programs, such as those conducted in the Northwestern Hawaiian Islands, will likely be required to minimize the damage wrought by abandoned, lost, or otherwise discarded fishing gear.

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Supplementary Materials

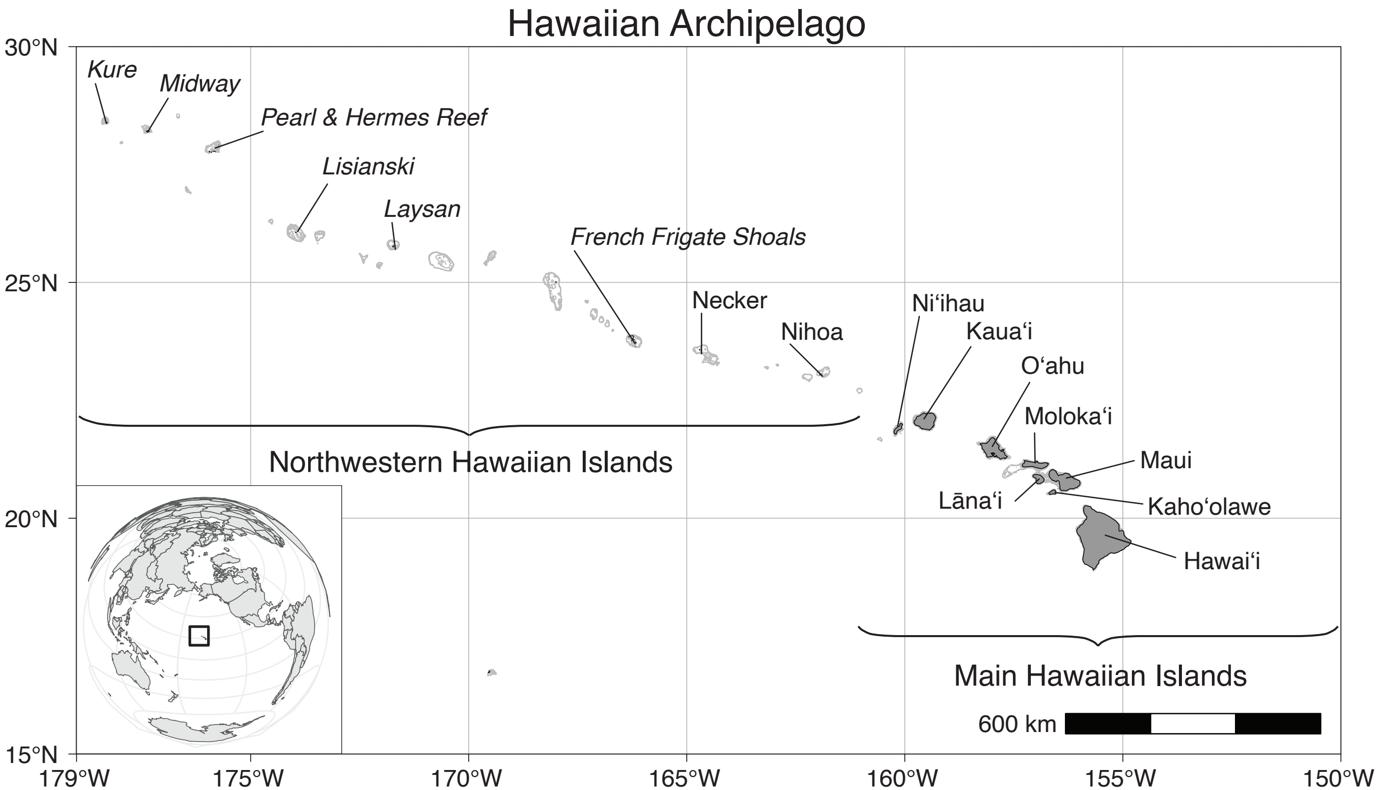
Materials and Methods
Tables S1 to S2
References (*40*—*48*)

Fig. 1. The Hawaiian Archipelago. In the Northwestern Hawaiian Islands, Hawaiian monk seal subpopulations (Hawaiian language place names in parentheses) are located at Kure Atoll (Hōlanikū), Midway Atoll (Kauaihelani), Pearl and Hermes Reef (Manawai), Lisianski Island (Kapou), Laysan Island (Kamole), French Frigate Shoals (Lalo), Necker Island (Mokumanamana), and Nihoa Island. Monk seals also occur throughout the main Hawaiian Islands. Monk seal subpopulations included in this study are labeled with italicized text.

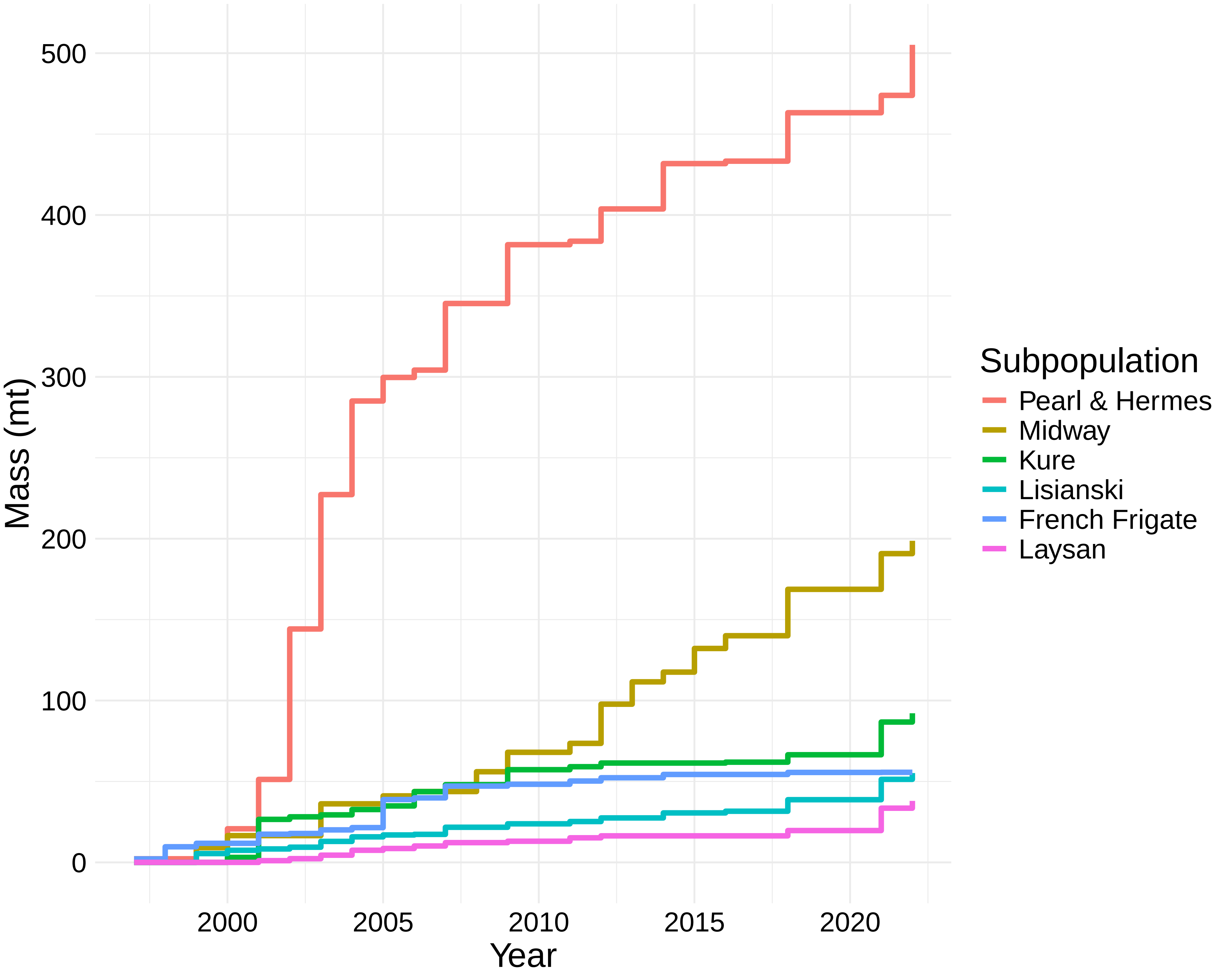
Fig. 2. Images of marine debris in the Northwestern Hawaiian Islands. (A) A weaned Hawaiian monk seal pup entangled in a derelict fishing gear mass at Pearl and Hermes Reef. The debris washed up next to an islet and U.S. National Oceanic and Atmospheric Administration (NOAA) biologists disentangled the pup. PHOTO: NOAA **(B)** A dive team carefully cutting debris away from a coral reef. **(C)** Hauling recovered debris into small boats**. (D)** Disentangling a Hawaiian green sea turtle discovered during debris removal operations. PHOTOS B, C, D: PMDPHAWAII.ORG

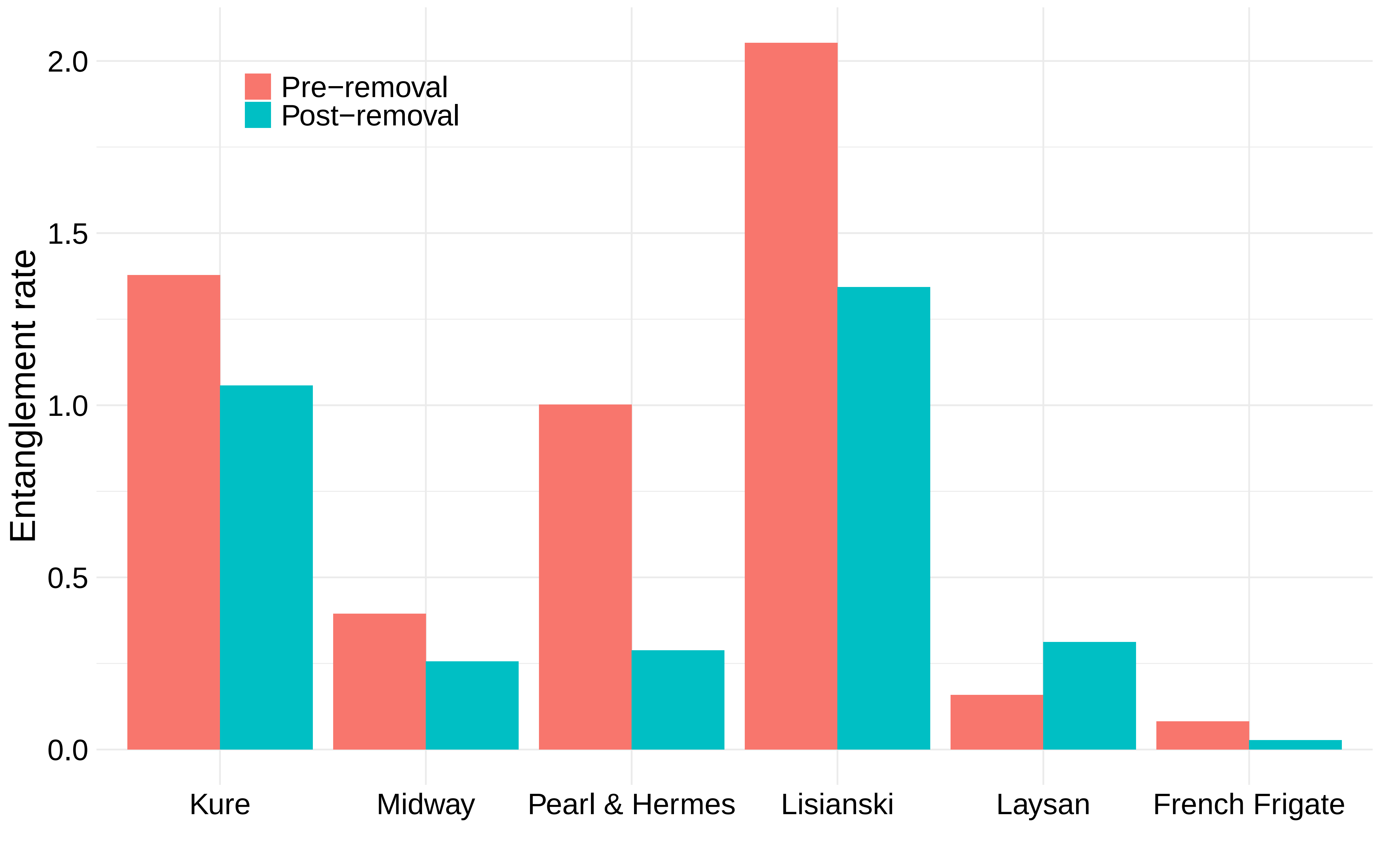
Fig. 3. Cumulative mass (mt) of marine debris removed by location in the Northwestern Hawaiian Islands by year.

Fig. 4. Weaned Hawaiian monk seal entanglement rate (per 1000 observed weaned pup exposure days) before and after initiation of large-scale marine debris removal. Subpopulations are ordered left to right in accordance with their relative location from northwest to southeast (Fig. 1). A statistically significant decline in entanglement rates occurred after marine debris removal began at Pearl and Hermes Reef.


Hawaiian Archipelago
30°N
25°N
20°N
15°N
179°W
175°W
170°W
165°W
160°W
155°W
150°W
Kure
Midway
Pearl & Hermes Reef
Lisianski
Laysan
French Frigate Shoals
Necker
Nihoa
Ni‘ihau
Kaua‘i
O‘ahu
Moloka‘i
Maui
Lāna‘i
Kaho‘olawe
Hawai‘i
Northwestern Hawaiian Islands
Main Hawaiian Islands
600 km


A
B
C
D
MILPRO


Mass (mt)
500
400
300
200
100
0
2000
2005
2010
2015
2020
Year
Subpopulation
Pearl & Hermes
Midway
Kure
Lisianski
French Frigate
Laysan


Pre−removal
Post−removal
Entanglement rate
2.0
1.5
1.0
0.5
0.0
Kure
Midway
Pearl & Hermes
Lisianski
Laysan
French Frigate