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Large floating abandoned, lost or discarded fishing gear (ALDFG) is frequent marine pollution in the Hawaiian Islands and Palmyra Atoll

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A B S T R A C T

Abandoned, lost, or discarded fishing gear (ALDFG) is a major source of marine debris with significant ecological and economic consequences. We documented the frequency, types, sizes, and impacts of ALDFG recovered from Hawai'i and Palmyra Atoll in the Central North Pacific Ocean (CNPO) from 2009 to 2021. A total of 253 events weighing 15 metric tons were recovered, including 120 drifting fish aggregating device (dFAD) components, 61 conglomerates, fewer distinct nets, lines, buoys, and unique gear. The Hawaiian Islands were dominated by conglomerates and Palmyra Atoll by dFADs. DFADs were connected to the Eastern Pacific tropical tuna purse seine fishery. Windward O'ahu experienced up to seven events or 1800 kg of ALDFG per month. Across Hawai'i, ALDFG was present on 55 % of survey days, including hotspots with 100 % occurrence. Coral reef damage, entangled wildlife, navigational and removal costs are reported. The data highlight the large magnitude of ALDFG and associated impacts in the CNPO.

1. Introduction

Marine plastic debris is a global and pervasive threat to marine ecosystems. Between 4.8 and 12.7 million metric tons of plastic enter the ocean each year (Jambeck et al., 2015). Plastic items persist in the environment for decades or centuries (Ward et al., 2019), creating lasting environmental concerns. The transportation and fate of plastic marine debris are greatly influenced by their polymer composition (Brignac et al., 2019). Items made from polymers denser than seawater, such as polyethylene terephthalate or nylon, sink quickly to the seafloor and remain closer to where they were lost or discarded. Items made of polymers less dense than seawater, such as polyethylene and polypropylene, unless weighed down by something denser, can drift long distances on the ocean's surface pushed by winds and ocean currents to wash up on sensitive habitats, such as coral reefs and beaches, like those in Hawai'i, far from sources (Barnes, 2005; Brown et al., 2005; Derraik, 2002; Macfadyen et al., 2009; Maximenko et al., 2018; Murray et al., 2018).

Abandoned, lost, or discarded fishing gear (ALDFG) is primarily plastic and makes up a large magnitude, but not well documented, percentage of marine debris. Determining accurate rates of fishing gear loss is challenging (Richardson et al., 2019, 2021). As early as 1975, an estimated 135,400 tons of ALDFG was dumped into the ocean by fishing fleets globally (Derraik, 2002). Decades later, Lebreton et al. (2018) and Macfadyen et al. (2009) estimated that ALDFG made up 10 % or 19.2 % of the global marine litter added to the ocean annually. Both Kuczenski et al. (2021) and Richardson et al. (2022) estimated that approximately 2 % of millions of metric tons of plastic fishing gear in use worldwide in the ocean is lost annually. The fisheries investigated included industrial trawl, purse seine, and pelagic longline, as well as gillnet, pot, and trap fisheries. The Great Pacific Garbage Patch (GPGP) holds the majority of the 96,400 metric tons of floating plastic pollution estimated to be in the

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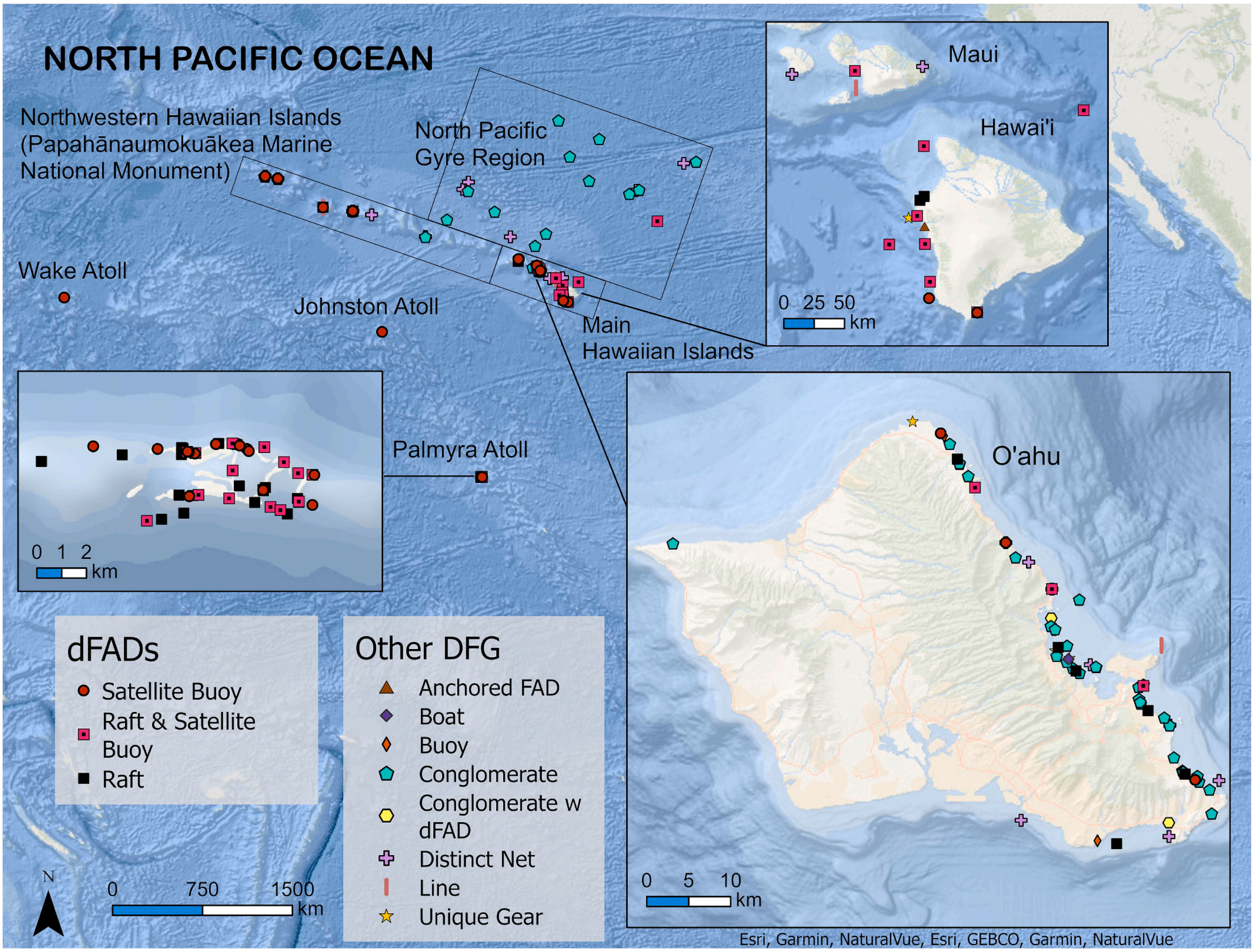


Fig. 1. Map of ALDFG events that had location coordinates and were recovered as marine debris from 2009 to 2021 in the main Hawaiian Islands, Papahānaumokuākea Marine National Monument, North Pacific Gyre Region, and Palmyra Atoll.

North Pacific Ocean (Eriksen et al., 2014). Specifically, in the GPGP, ALDFG comprises 46 % of floating plastic debris mass as fishing nets (Lebreton et al., 2018), 88 % of marine debris entangled on actively fished longline gear (Uhrin et al., 2020), and 75 % to 86 % of plastic marine debris items >5 cm (Lebreton et al., 2022).

The ecological and economic consequences of ALDFG are also substantial (NOAA Marine Debris Program, 2015), necessitating the development of regulations and best practices for managing fishing gear (Global Ghost Gear Initiative, 2021). Ghost fishing, or the ability of fishing gear to continue to fish after all control of that gear is lost (Smolowitz, 1978), of some commercial fish populations can result in millions of dollars of lost harvest (Drinkwin, 2022). ALDFG is the deadliest type of plastic pollution in the ocean for marine organisms, such as sharks, sea turtles, seabirds or marine mammals (Gilman et al., 2021; Wilcox et al., 2016). Entanglement and death of protected marine species have been documented for decades in the Hawaiian Archipelago, especially in the Papahānaumokuākea Marine National Monument (PMNM) in the Northwestern Hawaiian Islands (NWHI) (Boland and Donohue, 2003; Butterworth, 2016; Currie et al., 2017; Donohue and Foley, 2007; Duncan et al., 2017; Hyrenbach et al., 2020; Shomura and Yoshida, 1985; Timmers et al., 2005). Large conglomerates of ALDFG fragment, abrade, smother, and kill coral habitat as waves push the large debris across the reef towards shore (Donohue et al., 2001; Suka et al., 2020). ALDFG may also act as vectors for introducing invasive species and pathogens, and fragment to become available for ingestion by marine organisms (Bowley et al., 2021; Clukey et al., 2017; Gilman et al., 2021; Haram et al., 2021; Lusher et al., 2017; Therriault et al., 2018). As well, DFG imposes hazards on navigation (Beaumont et al., 2019; Hong et al., 2017; Uhrin et al., 2020). In 2015 alone, marine debris caused an estimated US$10.8 billion in damages to the Asia-Pacific Economic Cooperation economies (McIlgorm et al., 2020).

Many pelagic fish species naturally congregate under floating objects. Fishers have taken advantage of this behavior by constructing human-made floating objects to harvest and aggregate fish more easily (Castro et al., 2002) named fish aggregating devices (FADs). As a result, this phenomenon has been carefully and systematically exploited for decades to catch schools of commercially valuable fish such as tuna (Gershman et al., 2015; Scott and Lopez, 2014). These FADs can either be anchored (aFADs) or drifting (dFADs). DFADs are used heavily by the tropical tuna purse seine fishery (Lennert-Cody et al., 2018; Scott and Lopez, 2014). Each year, approximately 20,000 to 40,000 dFADs are deployed in the Western Central Pacific Ocean (WCPO) by the largest tuna fishery in the world (Escalle et al., 2021a), and 16,000 to 27,000 are deployed in the Eastern Pacific Ocean (EPO) (Lopez et al., 2022). Typically, tropical tuna dFADs are made of a floating bamboo raft ($\cong$ 1.5 m^2 square; occasionally made with PVC pipe instead) wrapped with dark plastic webbing or canvas; a submerged structure hanging from the raft to about 30–50 m deep on average consisting of plastic webbing, ropes or canvas; and a satellite-linked buoy that also contains an echo-sounder that allows a fishing vessel to return to a specific GPS

Table 1
Methods for detecting and documenting ALDFG in four Central North Pacific Ocean regions.

Region	Type of ALDFG	Years	Detection Methods	Effort
Palmyra Atoll (PAL)	dFADs	2009–2021	opportunistic during unrelated research or conservation efforts	<20 people at field station at any time
Main Hawaiian Islands (MHI)	dFADs	2014–2022	public reports; cleanup missions of many organizations	>100 s people
	all large ALDFG	2019–2021	public reports; cleanup missions of many organizations	>100 s people
	small and large of all types of ALDFG (method Section 2.4)	2019–2021	visual surveys aimed at finding ALDFG including more than monthly boat surveys along Kāneʻohe Bay reefs	161 d or 427 h by two co-authors
Northwestern Hawaiian Islands (NWHI)	dFADs	2015–2021	stockpile by field campers, directed cleanup missions	<20 people at each island at any time
	all large ALDFG, only a small selection was sampled	2020–2021	2 shoreline debris removal missions by PMDP, stockpile by field campers	20 people per mission, 3 weeks/ mission
Hawaiʻi Longline fishing grounds northeast of MHI (NPG)	all large ALDFG	2020–2021	opportunistic encounters by LL vessels at-sea, removals were monetarily incentivized	~13 vessels in the fleet participated

location to gather the catch when the biomass underneath the dFAD reaches a certain level (Lopez et al., 2014; Escalle et al., 2023). Because dFADs eventually drift outside of the fishing grounds, and retrieval is not practical, a substantial proportion is lost or abandoned every year (FAO, 2018). Despite recent efforts to move towards non-entangling biodegradable designs (e.g. Zudaire et al., 2023), dFADs can impact the marine environment by entangling wildlife and damaging fragile benthic habitats (Swimmer et al., 2020). Stranding or beaching events of dFADs have been reported across the Pacific Ocean (Escalle et al., 2022a, 2022b).

Due to its proximity to the GPGP, the Hawaiian Archipelago is disproportionately and heavily impacted by plastic pollution (NASEM, 2022). As currents push floating debris southwest from the GPGP towards the Hawaiian Islands, windward reefs and coastlines continually collect debris (Brignac et al., 2019; Miron et al., 2021). Yearly, hundreds of tons of plastic contaminate the shorelines of the Hawaiian Islands. Scientific documentation of the amount of contamination has focused on the uninhabited NWHI (Boland and Donohue, 2003; Dameron et al., 2007; Donohue et al., 2001; Timmers et al., 2005), but cleanup organizations such as Surfrider Kauaʻi and Hawaiʻi Wildlife Fund have removed up to 86 metric tons per year from just two Main Hawaiian Islands (MHI) (Berg et al., in review). Despite the wide-ranging impacts, ALDFG is underreported and systematic detection surveys are rare in Hawaiʻi (Moy et al., 2018, Berg et al., in review).

Here, we report the amounts and frequencies of large ALDFG events, including dFADs, washing ashore in the NWHI, MHI, and Palmyra Atoll (PAL), as well as recovered from the North Pacific Subtropical Gyre (NPG). With a total of 253 events recovered and methodically documented over ≅2.5 million km^2, the objective is to contribute to the knowledge gaps about the distribution, types, and magnitude of ALDFG events in the Central North Pacific Ocean (CNPO). This large ALDFG database and resulting findings will inform society of the magnitude of this kind of marine pollution and provide information to discuss strategies to prevent or mitigate the ecological and economic impacts of ALDFG in the CNPO.

2. Methods

2.1. Study regions

The remote Hawaiian archipelago in the CNPO is rich in biodiversity, including rare and endemic wildlife and essential coral reef habitats. The island chain extends >2400 km from Kure Atoll in the NWHI to the Island of Hawaiʻi in the MHI. The NWHI are uninhabited except for a small number of conservation and research personnel. The MHI host over 1.4 million residents and 9.2 million visitors per year. PAL is located 1600 km south of the Island of Hawaiʻi and near the northern end of the Northern Line Islands. It is a National Wildlife Refuge and part of the Pacific Remote Islands Marine National Monument with no commercial fishing allowed within the 50-nautical mile boundary. Palmyra's nearly pristine tropical coral reef habitat and large abundances of fishes, sea turtles, seabirds, and marine mammals are critical for the conservation of marine biodiversity in the Pacific Ocean.

2.2. Large ALDFG detection, removal, and collection

Large ALDFG events were recorded in four study regions: NWHI, MHI, NPG, and PAL (Fig. 1). In this study, a large ALDFG event is defined as an isolated single item or conglomerate of fishing gear found in the ocean or along the shoreline that is not being actively fished and ranges in size from a dFAD satellite buoy (33 cm in diameter) to large conglomerates (≦48 m long). The detection and removal of ALDFG were conducted on shorelines, reefs, nearshore waters, and open ocean by multiple organizations with methods that differed among the regions. Different time periods, levels of effort, and prioritization of certain types of ALDFG are summarized in Table 1. The differences were due to accessibility and research focus in each region. Effort was not documented during the ALDFG collections in this section of the study, so comparing ALDFG quantities across regions or time is not possible with these collection campaigns.

2.2.1. Palmyra Atoll (PAL)

The Nature Conservancy and the U.S. Fish and Wildlife Service (FWS) began documenting dFAD strandings at PAL in 2009. Documentation of ALDFG at PAL is focused only on dFADs, because other types of large ALDFG are rare. Frequent, opportunistic, and non-randomized surveillance was conducted along shorelines and nearshore reefs. Complete removal was conducted when possible.

2.2.2. Main Hawaiian Islands (MHI)

In 2014, documenting evidence of dFAD strandings or sightings began in the MHI in a database maintained by Hawaii Pacific University's Center for Marine Debris Research (CMDR). DFAD reports are collected opportunistically from public, social media posts, or through a network of marine debris cleanup organizations. From October 2019 through the end of 2021, a directed research project expanded the scope to documenting all types of large ALDFG with the goal to study the amounts, types, and sources in the MHI compared to the NWHI and NPG. The public reported the detection of ALDFG through social media, hotlines monitored by non-governmental organizations (NGOs), and an online form created by the Hawaiʻi Department of Land and Natural Resources (DLNR) Division of Boating and Ocean Recreation (DOBOR). In addition to the complete, rapid removals performed by the authors

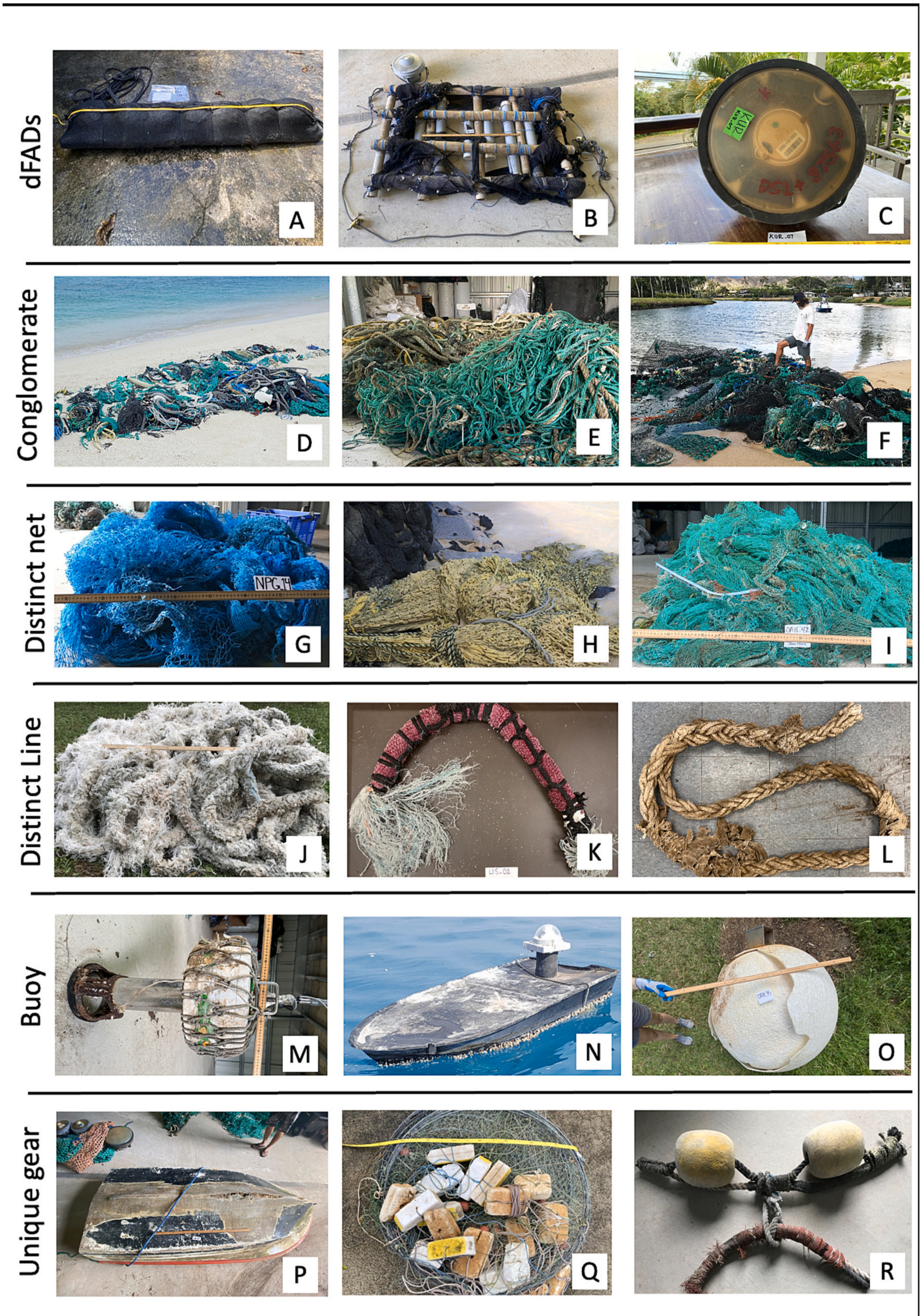


Fig. 2. Three examples of each large ALDFG event type recovered from the Central North Pacific Ocean: dFAD components, conglomerates, distinct nets, distinct lines, buoys not related to dFADs, and unique gear (defined in Table 2).

Table 2
Nomenclature and definition of the categories used to classify ALDFG events including conglomerate, distinct net, distinct line, buoy, unique gear, and dFAD.

ALDFG categories	Definitions
dFAD	Drifting fish aggregating device deployed by a sector of the tropical tuna purse seine fleet to aggregate tuna. When intact it consists of a floating raft with an appendage hanging several meters below the surface and a floating satellite-linked buoy that provides GPS location and sometimes fish biomass. Any piece of a dFAD found as marine debris was categorized as dFAD, even the satellite buoy.
Conglomerate	A tangled grouping of nets, lines, or other fishing gears that were not originally from a single fishing gear.
Distinct Net	A portion of an intact fishing net that was originally from a single fishing net. May consist of several sections of net tied together, but is independent of other tangled gear. May have some tangled debris but the majority of the mass and volume are from a distinct original net.
Distinct Line	A rope or cord used for fishing or maritime operations.
Buoy	A buoyant item that is used to mark a location, serving navigation, drift detection, mooring, or visual indicator function. Original use could be either anchored or drifting, but this category did not include any satellite buoy related to dFADs. Two anchored FADs were included in this category.
Unique Gear	Fishing gear or a piece of fishing equipment with distinct characteristics not matching other ALDFG categories. One dinghy boat was included in this category.

(53 ALDFG events), multiple marine debris cleanup NGOs in the MHI reported, removed, and provided 23 ALDFG to this project.

2.2.3. Northwestern Hawaiian Islands (NWHI)

In 2015, dFAD sightings or strandings in the NWHI began being documented in the dFAD database. Before 2020, dFADs, mostly only satellite buoys, were opportunistically collected and stockpiled by field campers at the research stations in this remote region. The amount of ALDFG washing into the reefs and shorelines of NWHI necessitates frequent cleanup missions. The NGO Papahānaumokuākea Marine Debris Project (PMDP) runs dedicated missions. Each PMDP 3 to 4-week mission on a merchant vessel travels from Honolulu to multiple islands in PMNM where 16 crew members remove ≅50 metric tons of marine debris, most often large ALDFG events, from shorelines and reefs. ALDFG events from two missions were selected with the following criteria. From the October 2020 mission, all large ALDFG events encountered along the shoreline of Tern Island in a three-day period were included; along with one event found snagged on coral and entangling a monk seal pup nearshore Kure Atoll. From the April 2021 mission, at least three ALDFG events were selected from the intertidal region of each of four islands (Laysan, Lisianski, Midway, Kure) with a bias towards conglomerates or distinct nets that were > 45 kg each or unique ALDFG. Most dFADs observed on this mission were collected for this study. The events were tagged with date and location found and stored isolated from other marine debris aboard the ship.

2.2.4. North Pacific Subtropical Gyre (NPG)

In the pelagic waters northeast of the MHI, the Hawai'i longline fishers frequently observe ALDFG floating at-sea, and it often entangles their gear or vessels (Uhrin et al., 2020). Thirteen longline vessels removed and delivered large ALDFG events to O'ahu, incentivized through a bounty project paid from research grant funds at $1 per dry pound.

2.3. Large ALDFG database creation

For each ALDFG event, date, location, environmental damage, ALDFG type, dimensions, and dry mass among other information were recorded in a database (Table S1). ALDFG types were categorized as conglomerates, distinct nets, distinct lines, buoys not related to dFADs, unique gear, and dFAD components (Fig. 2, Table 2). Fishing floats found alone were sometimes, but not always, included in the database; thus, they were excluded from this paper. The make, model, markings, and identification numbers of dFAD satellite buoys were recorded. Early in the study we were unable to weigh events because of limited storage space and time before removal partners discarded them and lack of a scale. On these occasions, dry mass was estimated using linear regressions with dimensional measurements described in McWhirter (2022). Fishing gear items from each event were dissected, labeled as separate samples, individually measured, and polymer identified following specific protocols (McWhirter, 2022). Detailed results from these gear items (sample level) will be presented in future publications. This paper summarizes the findings at the event level.

2.4. Surveillance for ALDFG in MHI

An additional dataset was curated and analyzed to provide preliminary ALDFG quantities per unit effort. In this dataset, we documented 427 h of surveillance effort aimed at finding ALDFG over 161 d in the MHI from November 2, 2019, until December 31, 2021. More details about the surveillance methods and results can be found in *Supplementary Information and Table S2*.

2.5. Data analysis

Various detection and removal methods were required to accomplish this large-scale, multi-organization study. Methods were heavily dependent on logistics, personnel available, and removal operation protocols for given organizations. Careful selection of particular ALDFG events from the database was, therefore, necessary for certain analyses to minimize bias. For example, to assess seasonal or temporal variability in the frequency of ALDFG events, only events from O'ahu between May 2019 and December 2021 were selected. The project had relatively consistent effort over this timeframe and O'ahu offered year-round detection.

An external database was searched for the deployment date and location of 30 recovered dFAD satellite buoys made by Marine Instruments. The database contains satellite buoys deployed worldwide since 2014. When the deployment year, but not the month, was known, the range of possible months between deployment and discovery as marine debris was calculated and the median was used for data analysis. JMP 14.3.0 software was used for statistical testing.

3. Results and discussion

3.1. Large ALDFG events

A total of 253 ALDFG events were recovered and documented from all regions between 2009 and 2021 (Fig. 1), totaling ≅ 15 metric tons. The event level data are provided in Table S1. Most of the events were dFAD components (151 individual dFAD events and two conglomerates containing dFAD parts). Of these 153 dFAD-associated events, 72 were only the satellite buoy, 48 were only rafts, and 33 were rafts still connected to a satellite buoy. Two dFAD satellite buoys were found on Johnston Atoll and Wake Atoll, which are U.S. National Wildlife Refuges outside of the four large study sites. Conglomerates and distinct nets were the second and third dominant event types, with 61 and 25 events, respectively. Less common event types were seven unique gear events, five buoys (including two aFADs), and four distinct lines. Of the 14.7 metric tons that were weighed (149 ALDFG events), 71 % of the mass was from conglomerates, 14 % from distinct nets and 10 % from dFADs (Table 3). The average ALDFG event weighed 98.7 kg and conglomerates averaged 170 kg with a range from 3.0 kg to 1614 kg. The conglomerates were estimated to be on average 1.95 m^3 in volume with a range of 0.06 m^3 to 27.8 m^3. We can hypothesize only two ways conglomerates form, either different pieces of gear are intentionally tangled

Table 3
Mass and volume of large ALDFG events removed from the Central North Pacific Ocean.

ALDFG Event Type	n	Mass (kg)					n	Volume (m^3)				
		Total	Average	SD	Min	Max		Total	Average	SD	Min	Max
Conglomerate	61	10,387	170	256	3.00	1614	61	119	1.95	3.90	0.06	27.8
Distinct Net	25	2042	81.7	88.5	0.40	315	14	21	1.49	1.58	0.24	5.41
dFAD raft & satellite buoy	12	674	56.1	34.7	6.80	119						
dFAD raft	15	619	41.3	22.0	7.00	65.0						
dFAD satellite buoy	21	177	8.44	3.16	2.50	19.9						
Distinct Line	4	329	82.1	81.6	13.2	200	1	1.1	1.12			
Buoy (not related to dFADs)	4	165	41.3	31.8	12.4	82.0						
Unique Gear	7	311	44.4	100	0.147	271						
All types	149	14,703	98.7		0.15	19.9	76	141	1.9		0.06	5.4

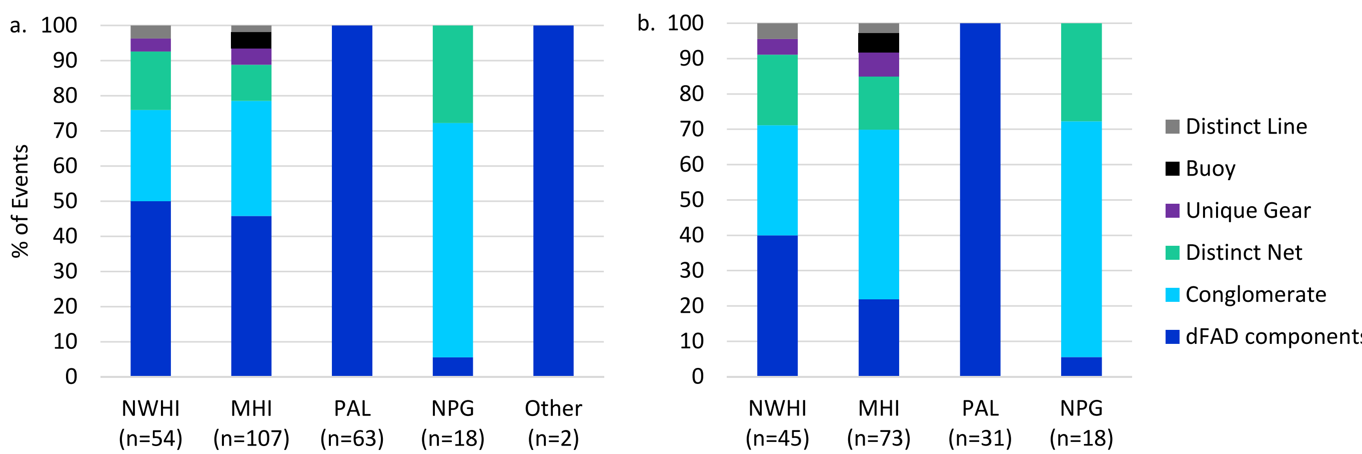


Fig. 3. ALDFG event types documented in the regions of the Central North Pacific Ocean a) within the entire database and b) standardized to only events found between Oct 2019 to Dec 2021. Regions include the Northwestern Hawaiian Islands (NWHI), Main Hawaiian Islands (MHI), Palmyra Atoll (PAL), North Pacific Gyre (NPG) and two events from Wake and Johnston Atolls (Other).

together by people, perhaps for makeshift FADs, or they tangle in the ocean. We believe the latter is more likely because we observe haphazard twists, lines that are snaked through other gear in complicated ways, and frayed ends of lines hooked into the frayed ends of other lines.

The dominance of dFADs, net conglomerates, and distinct nets was not surprising. The partners in the Hawaiʻi Marine Debris Action Plan have found and removed this type of marine debris for decades (NOAA Marine Debris Program, 2021). More detailed information regarding the polymer composition (Corniuk et al., in press) and sources of these ALDFG events will be included in future publications. Since the largest number of ALDFG events were dFADs, most events could be sourced to the tropical tuna purse seine fishery, but most of the ALDFG mass came from mid-water and bottom trawling fisheries that do not operate from Hawaiʻi. Since the gear floats, it drifts from faraway places to these remote island regions. Notably, our detection is not a full picture of all ALDFG in the CNPO because only floating gear was studied. Sinking gear found on the seafloor, such as nylon monofilament fishing line that commonly litters Hawaiian coral reefs or nylon netting that routinely makes up dFAD tails which are lost before they are found in Hawaiʻi, should receive attention in future studies.

3.2. Large ALDFG by region

Most events were recovered in the MHI (n = 107) followed by 63 from PAL, 54 from NWHI, and 18 from the NPG (Fig. 1). Greatest effort took place in the MHI because of the year-round 1.4 million residents, a network of cleanup organizations, and the location of most of the authors. For this reason, the largest number of events were documented in the MHI, specifically on O'ahu, the most populated of the MHI. The vast majority of the O'ahu events were concentrated on the east, or windward, shoreline (Fig. 1), which agrees with previous studies that showed greater accumulation of marine debris on windward compared to leeward shorelines of the MHI (Brignac et al., 2019; Moy et al., 2018). The marine debris on the windward shorelines was less dense, severely weathered, and not generated locally, providing evidence that a high proportion of the debris in the MHI is floating in from distant sources (Brignac et al., 2019). Physical oceanography models (Maximenko et al., 2018; Miron et al., 2021) and these results support the hypothesis that floating ALDFG travels from the GPGP to the MHI. Leeward vs. windward sides of other MHI should not be compared in Fig. 1 because of lesser effort on these islands.

ALDFG event types differed across regions (Fig. 3a), but this comparison is also biased by different methods across regions. The least biased regional comparison of ALDFG event type is from events found only between October 2019 to December 2021, the period of greatest effort to seek large ALDFG samples for a sourcing study (Fig. 3b). During this time, we actively removed both dFADs and other ALDFG types. The category proportions shown for the MHI are representative of typical ALDFG recovered from this region, but proportions in the NWHI and PAL may be somewhat skewed due to ALDFG type selectivity and because of the small sample in NPG. The PAL events were exclusively dFAD components, whereas dFAD events made up only 22 % of the MHI and 6 % of the NPG events (Fig. 3b). A dominance of dFADs was expected at PAL because of its proximity to the fishing grounds. dFADs are deployed by the tropical tuna purse seine fishery primarily between 10°N and 10°S across the Pacific Ocean (Escalle et al., 2021b; Lopez et al., 2022), latitudinally closer to PAL than MHIs. dFADs represented 40 % of the NWHI events (Fig. 3b), but this was due to biased event selection towards dFADs. From our experience, dFADs do not represent

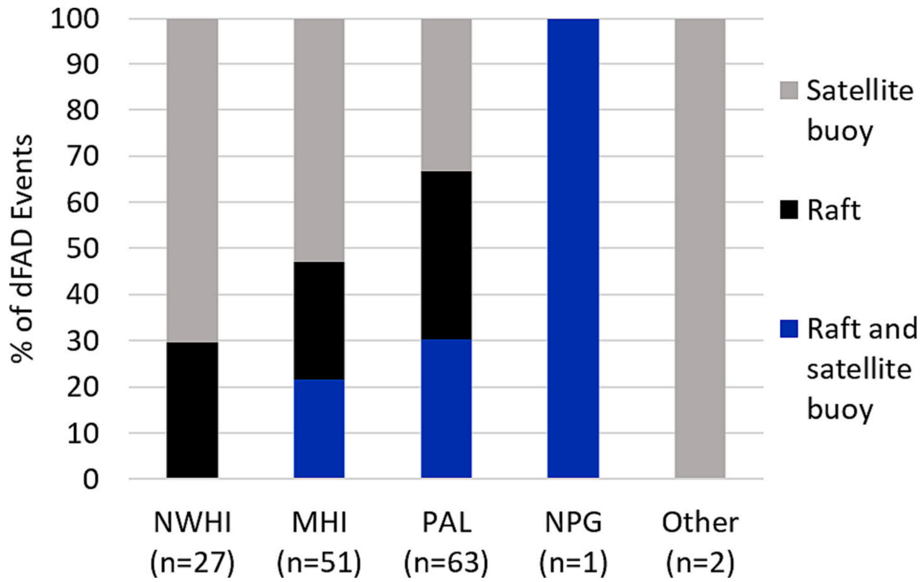


Fig. 4. Percentage of dFAD events found as marine debris in the Central North Pacific Ocean with the raft still connected to the satellite buoy compared to those found as an individual separated part. Regions include the Northwestern Hawaiian Islands (NWHI), Main Hawaiian Islands (MHI), Palmyra Atoll (PAL), North Pacific Gyre (NPG), and two events from Wake and Johnston Atolls (Other).

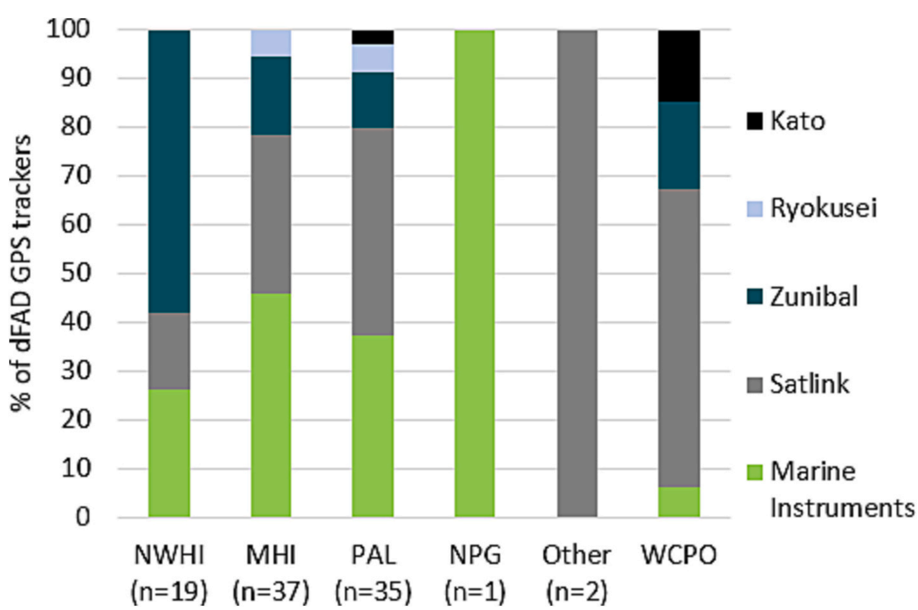


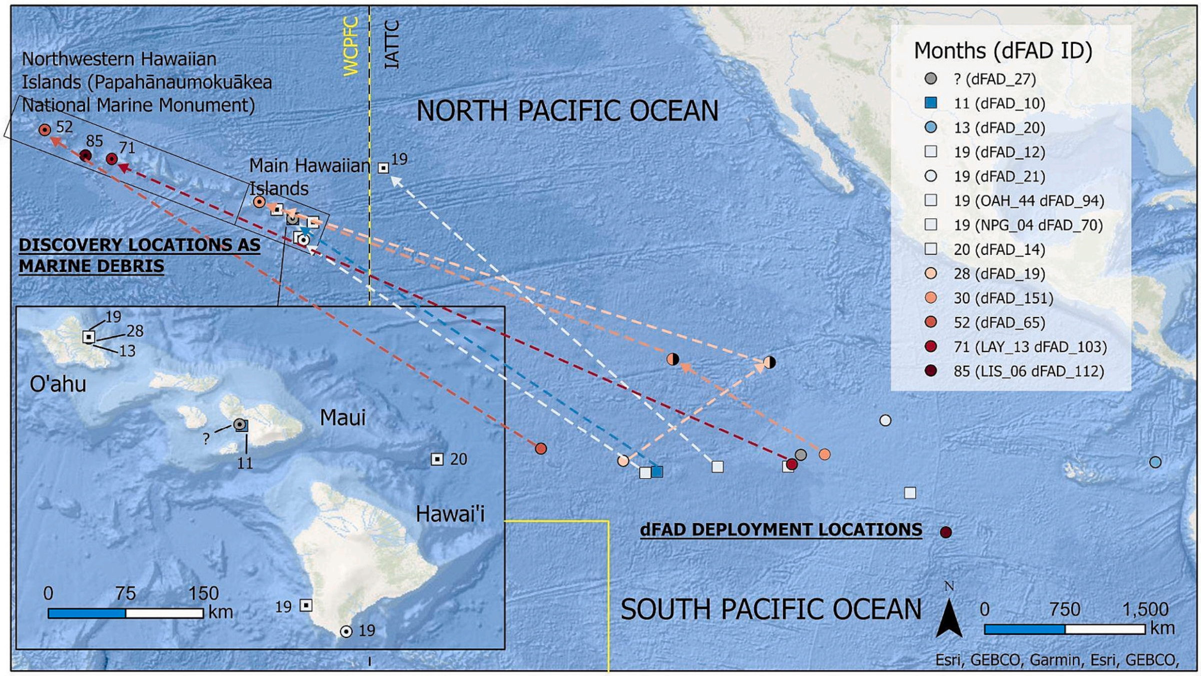
Fig. 5. Percentage of manufacturers of dFAD satellite buoys found as marine debris in the Central North Pacific Ocean. Regions include the Northwestern Hawaiian Islands (NWHI), Main Hawaiian Islands (MHI), Palmyra Atoll (PAL), North Pacific Gyre region (NPG), and two events from Wake and Johnston Atolls (Other). For comparison the proportional use of buoy manufacturers averaged across 2016–2020 in the Western Central Pacific Ocean (WCPO, Escalle et al., 2021b) is shown.

this large percentage of ALDFG found in the NWHIs, rather conglomerates are the dominant type. Conglomerates were also the most dominant event type in the MHIs (48 %) and NPG (67 %) followed by distinct nets (20 % in NWHI, 15 % in MHIs, and 28 % in NPG).

3.3. dFAD events

Across the regions, the percentage of dFAD events found with the raft still connected to a satellite buoy decreased with latitude when examining only the regions with more than three events (Fig. 4). Thirty percent of the dFAD events at PAL had rafts still connected to a buoy, whereas only 22 % were in this condition in the MHIs and none in the NWHIs. The distance, and thus longer arrival time, from equatorial deployment regions likely results in the degradation and separation of dFAD parts, especially the largest portion of dFADs, the tails. Very few recovered dFADs still contained tails. The location of lost tails is often unknown, but evidence of the tails snagging on nearshore benthic habitats like coral reefs was documented in this study (see Section 3.6). If lost in deep water, the tails, usually made of nylon netting or weighted with metal, sink and would litter the seafloor. To our knowledge the presence of dFAD tails on the seafloor has not been documented.

The dFAD satellite buoys found across the CNPO were mainly from three manufacturers: 38 % Marine Instruments, 34 % Satlink and 22 % Zunibal, with smaller proportions from Ryokusei (4 %) and Kato (1 %) (Fig. 5). These percentages differ from those deployed from 2016 to 2020 in the WCOP (Escalle et al., 2021b), where a lesser percentage of Marine Instruments and a greater percentage of Satlink buoys were deployed. The composition of different manufacturers arriving as a.



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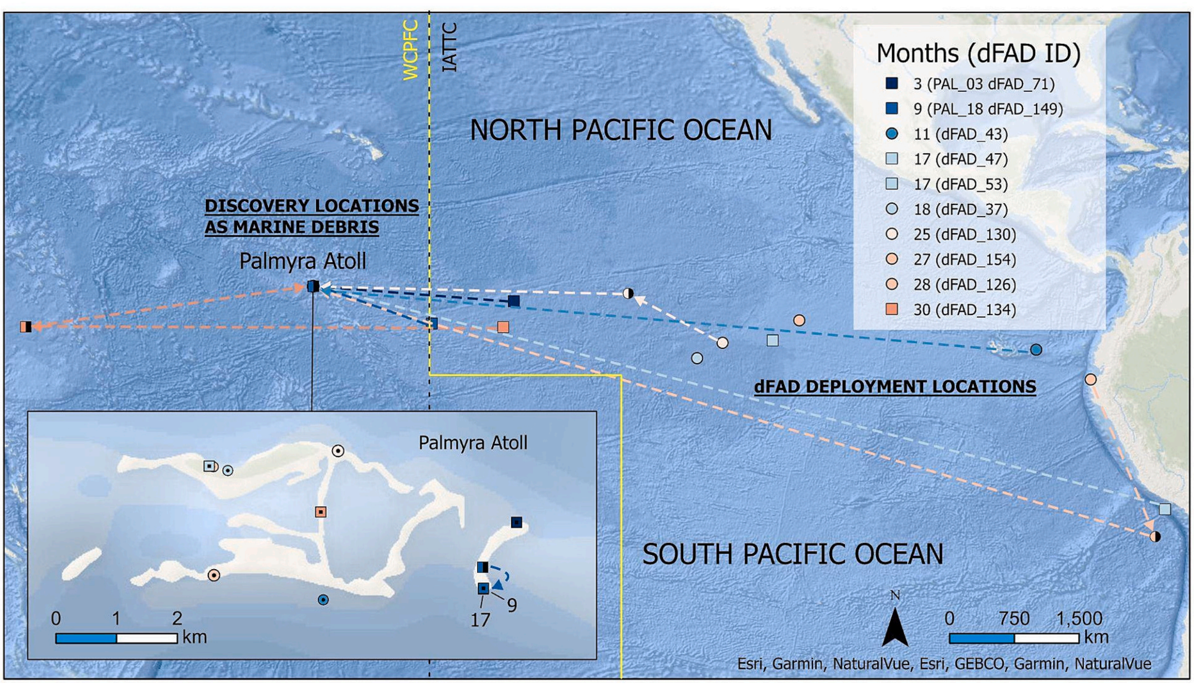
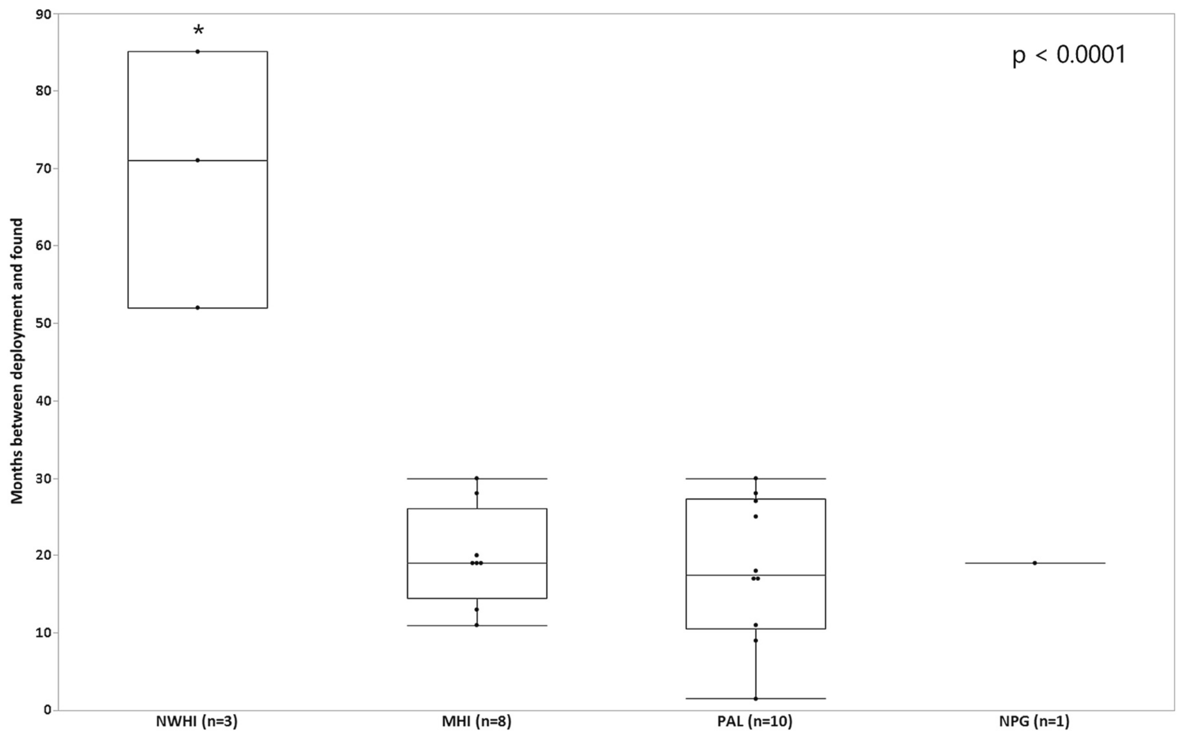
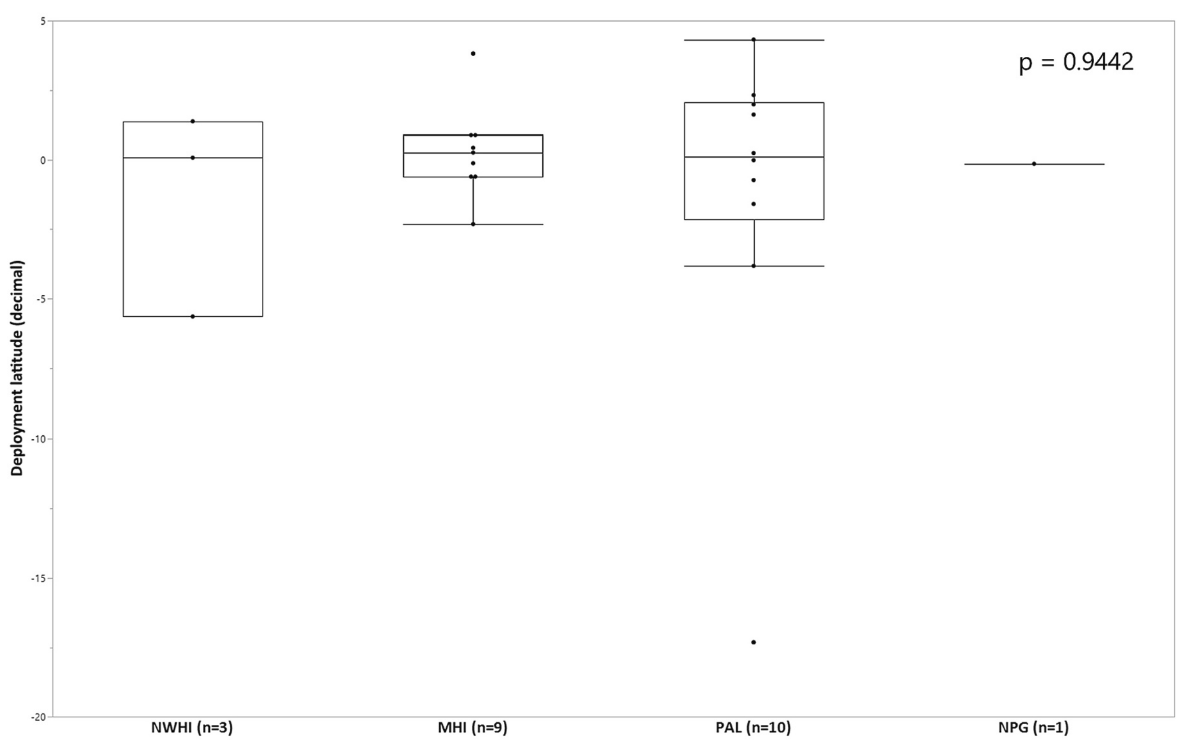


Fig. 6. Locations of individual dFADs from deployment to discovery as marine debris in a) the Hawaiian Islands and b) Palmyra Atoll. The colors depict the duration between deployment and discovery in months with blues as the shortest and reds as the longest. Squares indicate dFAD rafts still attached to a satellite buoy upon discovery; circles indicate the satellite buoy was discovered alone. Empty markers are deployment locations, half-filled markers are deactivation locations, and dots within the marker indicate the discovery locations. The arrows show examples of connectivity from deployment, deactivation, and discovery; these are not drift trajectories.



a.



b.

Fig. 7. Deployment origins of dFAD satellite buoys that were found as marine debris in the Central North Pacific Ocean, including the a) months between dFAD deployment and recovery, b) deployment latitudes, and c) deployment longitudes. Regional differences were tested with ANOVAs followed by Tukey multiple comparison tests (months and longitude) or Wilcoxon test (latitude) in JMP software. The asterisk indicates a significant difference from the other regions. Removal regions were Northwestern Hawaiian Islands (NWHI), Main Hawaiian Islands (MHI), Palmyra Atoll (PAL), and North Pacific Gyre (NPG).

marine debris in these regions could result from the combination of multiple factors: the composition deployed in certain regions in certain years, the durability of the satellite buoys, and windage/drift patterns.

Marine Instrument dFAD buoy IDs were searched through a database for deployment information. Of the 30 dFAD satellite buoys searched, deployment year and months were found for 24 (80.0 %), deployment locations were revealed for 23 (76.7 %), and deactivation locations were determined for 6 buoys (Table S1). All search results showed

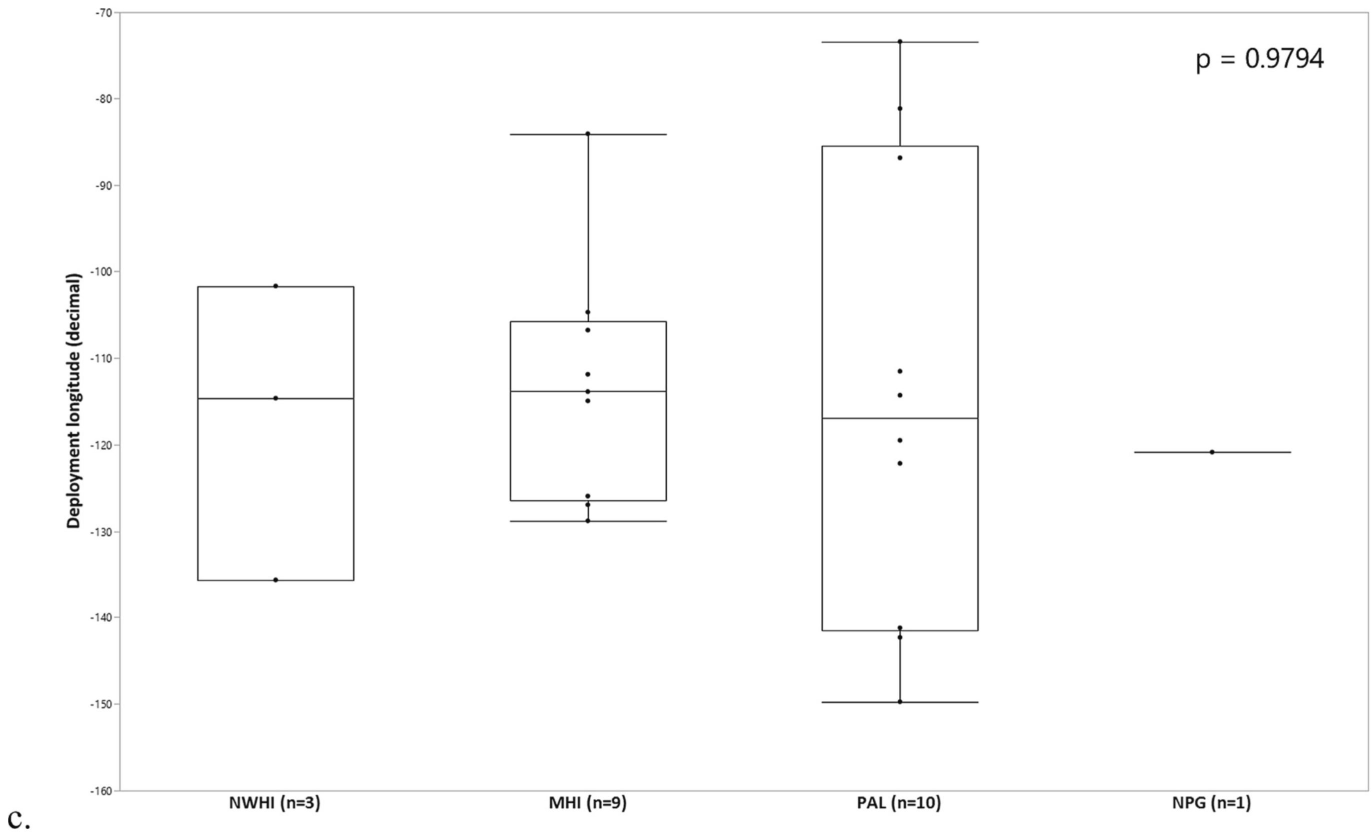


Fig. 7. (*continued*).

deployment locations within the EPO (Fig. 6), suggesting that these remote island regions are primarily connected with the EPO fleets. In another study, simulated drift trajectories of dFADs showed greater connectivity of Hawaiʻi with the EPO than the WCPO (Escalle et al., 2022c).

Months between deployment and deactivation by the fishers ranged from one to 19 with a median of four months. Months between deployment and discovery/removal as marine debris ranged from <3 months to 85 months (Table S1; Fig. 6). Most dFADs arrived in the MHI and PAL less than two years after deployment (Fig. 7a). The dFAD satellite buoys recovered from the NWHI were at sea for a significantly longer time (average of 69 months) than the other three regions (ANOVA F ratio = 24.3, 3 d.f., $p < 0.0001$; Fig. 7a). The deployment latitudes of the identified dFADs ranged from 4.3°N to 17.3°S (Figs. 6 and 7b), and longitudes ranged from 73.4°W to 149.7°W (Fig. 7c). The original deployment latitudes or longitudes of dFADs did not differ significantly among the four arrival regions (Wilcoxon or ANOVA, $p < 0.05$).

Significant data gaps exist in the distribution and frequency of lost dFADs. Many options are available (not without challenges) to reduce losses of dFADs and impacts of these losses. With tens of thousands of dFADs deployed each year (Gershman et al., 2015), even low rates of gear loss can result in large numbers of lost FADs globally (Maufroy et al., 2015). Remote islands in the CNPO experience dFAD arrivals with environmental damages. Monitoring and documenting dFADs arrivals through visual detection is challenging. The drift trajectories of satellite buoys are confidential data shared only between the tracker manufacturer and the fishing vessel client. Since data streaming of locations often has a daily cost, vessels activate particular satellite buoys for short periods of time to determine their present location. Once dFADs drift outside of their fishing grounds, the vessels deactivate the satellite buoys. The Parties to the Nauru Agreement (PNA) in the WCPO now require dFAD reporting and tracking, and the Inter-American Tropical Tuna Commission (IATTC) requires vessels to provide FAD data and marking information (National Research Council, 2009; Escalle et al., 2018; Gershman et al., 2015). These tracking programs could provide information for dFAD loss estimates. Furthermore, some fishers on their way back to port are disincentivized to collect wayward dFADs because they are charged by vessel owners for each fishing day. Any change in speed or direction signals a fishing day, even if the vessel is retrieving an object rather than setting on it. Additionally, voluntary collaborative programs proactively monitor dFAD movements to prevent dFAD strandings and associated environmental impacts. For example, the Palmyra dFAD Watch Program was recently established (Miller, 2022). This program tracks the location of and biomass under dFADs throughout the blue water marine protected area (BWMPA) surrounding PAL. This first-of-its-kind program in the Pacific Ocean fills knowledge gaps about the impact of dFADs on protected blue water and coastal ecosystems, while also alerting staff on the atoll of opportunities to intercept and recover dFADs prior to their grounding on the fragile coral reefs.

3.4. Large ALDFG frequency

The frequency of ALDFG events was only assessed on O'ahu because the authors and the general public (1 million residents) provide year-round detection efforts. Even so, the detection efforts are far from saturation reporting, and removals by the general public and other organizations occur without the authors' knowledge. The number of ALDFG events per month ranged from zero to eight with a peak in April 2021 (Fig. 8a). From September 2019 to December 2021, during the majority of our efforts, the median was 2.00 events/month with an average ± one standard deviation of 2.11 ± 2.04 events/month. ALDFG dry mass removed from O'ahu ranged from zero to 1836 kg/month (Fig. 8b) with a peak in September 2020 due to a single 1614-kg conglomerate. The second highest month was December 2020, in

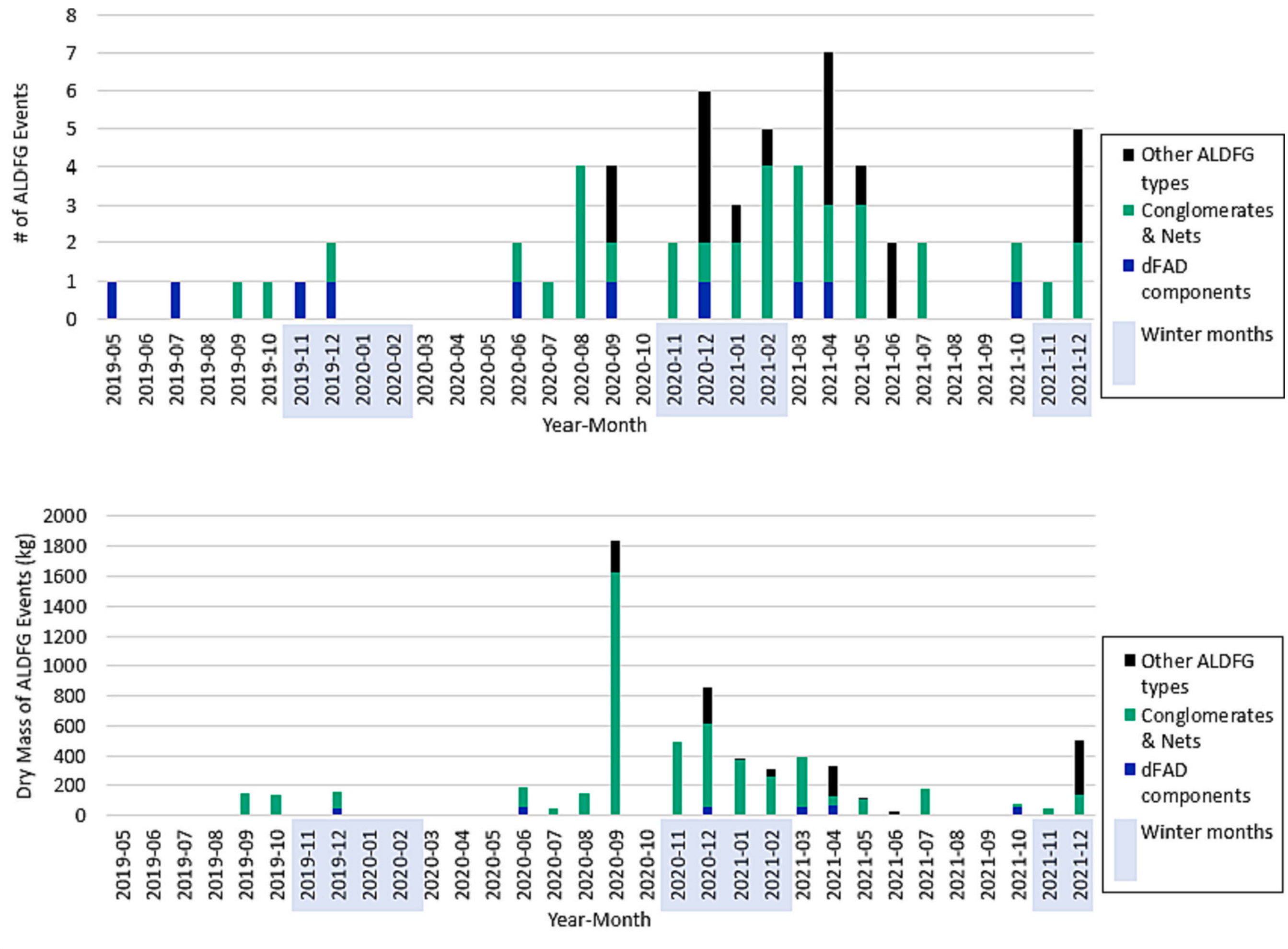


Fig. 8. ALDFG events removed from or near O'ahu, Hawai'i, in a) event numbers per month and b) dry mass per month. Other ALDFG types include distinct lines, buoys, or unique gear.

which three distinct nets and one conglomerate were removed, totaling 855 kg. From September 2019 to December 2021, the median, average, and one standard deviation was 128, 228, and 376 kg/month, respectively. A seasonal pattern was not evident in our data (Fig. 8), interannual patterns may be more important as observed on the islands of Kaua'i and Hawai'i (Berg et al., in review). These long-term monitoring programs showed that the mass of nets washing ashore on those islands peaked from 2017 to 2019, a few years before our study on O'ahu began.

3.5. ALDFG surveillance results in MHI

The documented surveillance effort in the MHI was focused primarily on O'ahu and Maui and did not include other hotspots of marine debris accumulation within the state, notably Kamilo on the Island of Hawaiʻi and the east shores of Kauaʻi (Brignac et al., 2019; Berg et al., in review). This preliminary exercise was intended to provide the first ALDFG quantities per unit effort in Hawaiʻi. Normalizing to effort allows for better geographic comparisons and understanding of the magnitude and frequency of this pollution.

During 161 days of documented surveillance efforts in the MHI, an average of 10.4 kg/day of marine debris was removed, totaling >1600 kg (Table S2, Fig. 9). Across the surveyed islands, marine debris of all types was detected on 74 % of survey days, whereas ALDFG, in particular, was detected on 55 % of survey days. ALDFG was fairly omnipresent across the studied islands at moderate to high frequency of occurrence, but the quantities of marine debris are strikingly different between the sides of the same island (Table S2, Fig. 9). The east side of O'ahu had the greatest mass of marine debris available to remove per day (18.6 kg/day), compared to <1 kg/day on O'ahu's west and south sides. This finding is the result of the windward (east) sides receiving large amounts of floating plastic debris that do not originate from Hawaiʻi or Hawaiian fisheries. Instead, large conglomerates of nets and lines made of floating polyethylene and polypropylene accumulate in the GPGP (Lebreton et al., 2018; Uhrin et al., 2020) from non-Hawaiian sources and then wash into Hawaiian waters, striking the windward reefs and shorelines (Brignac et al., 2019; Maximenko et al., 2018; Moy et al., 2018; Miron et al., 2021; Ribic et al., 2012). In contrast, the leeward sides are more protected from this source of pollution but receive significantly smaller amounts of debris notably from people in Hawaiʻi (Brignac et al., 2019). Hook and line fishing is widespread throughout the Hawaiian Islands (Wedding et al., 2018), resulting in locally-sourced ALDFG being omnipresent (Fig. 9 left panel). This type of ALDFG is typically nylon monofilament lines (sinking polymer) attached to metal weights, resulting in the gear sinking where it was lost. The vast differences in ALDFG types removed from windward vs. leeward sides are shown in Fig. S1 photographs.

3.6. ALDFG ecological and economic impacts observed

This study focused on floating ALDFG, most of which does not originate from fisheries in Hawaiʻi but harms the coral reef habitats surrounding the HI and PAL. Fourteen percent of the events were

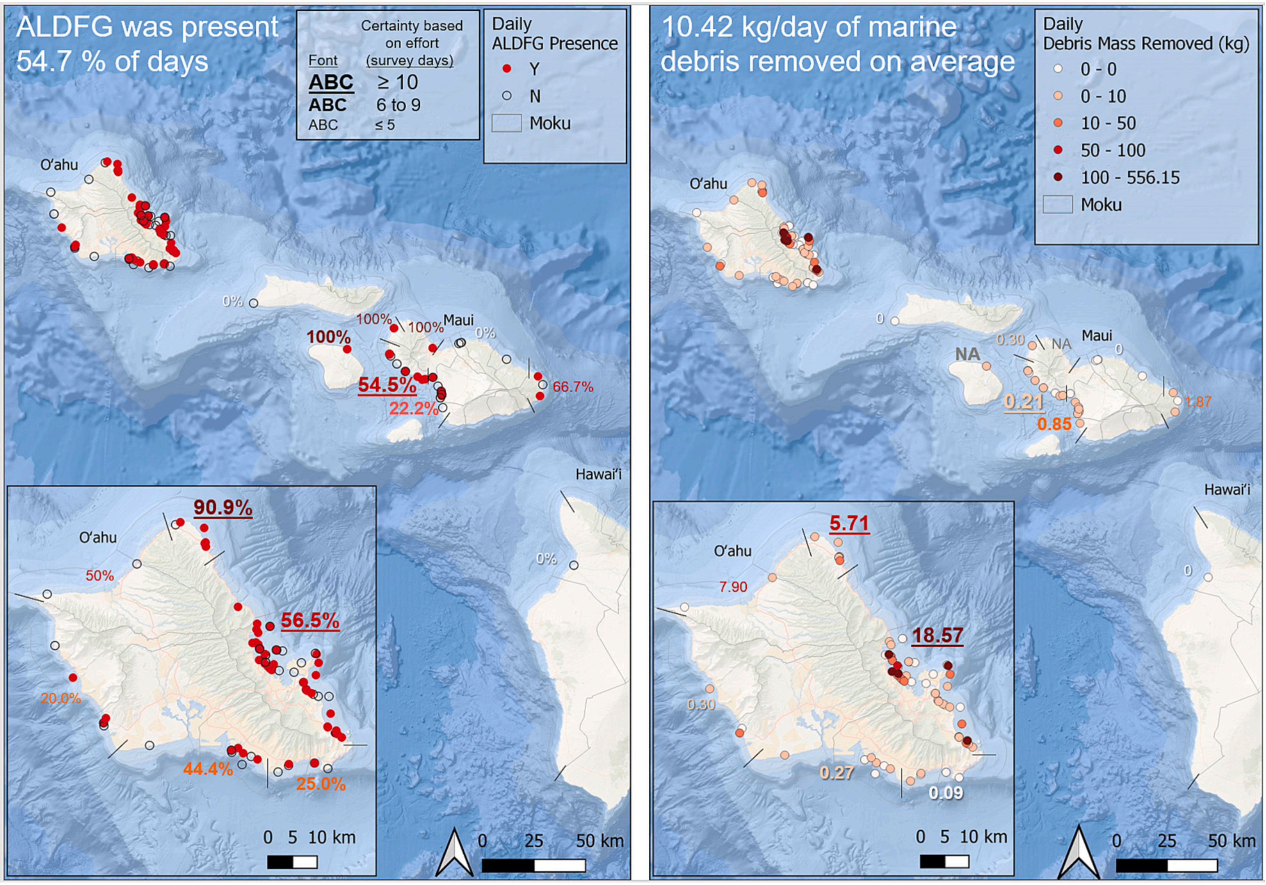


Fig. 9. Map of surveillance results for marine debris and ALDFG on five Main Hawaiian Islands. Markers on the map indicate a day of surveillance. Gray lines border the mokus, or Hawaiian traditional land management areas from mountain ridge to reef. Black lines indicate transitions between different sides of each island, which are based on mokus and the divisions used by Moy et al. (2018). Values shown on the left map are the frequency of occurrence of ALDFG along each island side, as a percent of surveillance days with ALDFG being present. Values shown on the right map are quantities of marine debris removed per survey day along the sides of each island, as the average mass of marine debris removed per survey day.

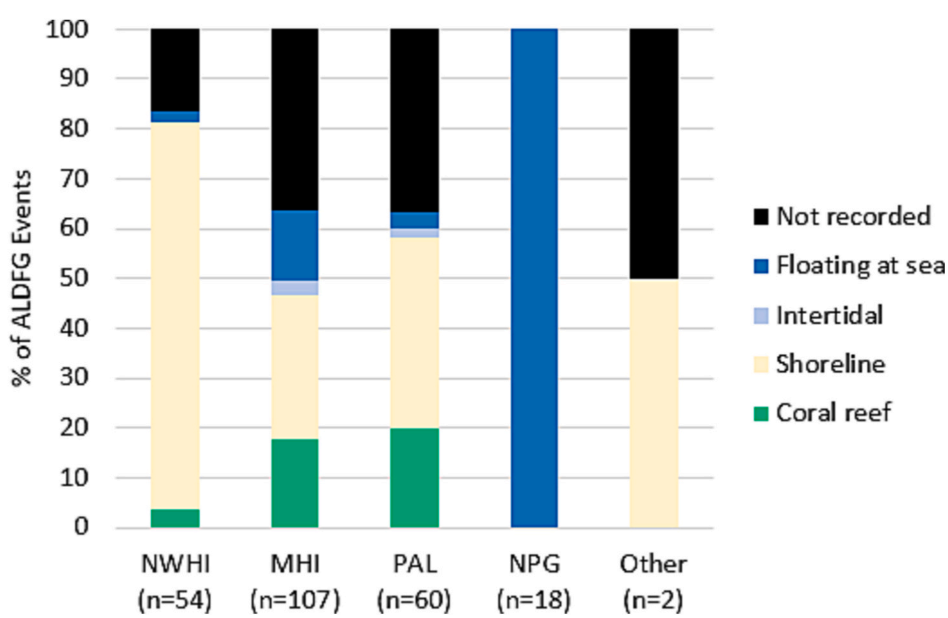


Fig. 10. Percentage of environments where ALDFG was found as marine debris in the Central North Pacific Ocean. Regions include the Northwestern Hawaiian Islands (NWHI), Main Hawaiian Islands (MHI), Palmyra Atoll (PAL), North Pacific Gyre (NPG), and two events from Wake and Johnston Atolls (Other).

snagged on coral reefs (Fig. 10), which results in substantial and long-lasting coral habitat damage. The majority were found on the shoreline (40 %), presumably after the coral reef damage had occurred as the ALDFG struck, tumbled, and smothered coral on its path towards the shore. Finding and removing floating ALDFG while still in deep water can prevent this damage, and 15 % of the ALDFG events in this study were found floating and removed at sea. Most of these were the result of an incentive project in which the Hawaiʻi-based longline fishing fleet was paid a bounty to remove and bring back ALDFG from their distant, pelagic fishing grounds.

Coral reef damage was estimated visually for 25 of the 33 events that were found on coral. Damage was defined as surface area of the reef that was covered or fragmented by the ALDFG or along the path where the ALDFG moved towards the shore. Visual estimates were performed by experts in assessing benthic coverage of coral reefs. The surface area of coral reef damage ranged from 0.2 m^2 to 250 m^2 per event with a median, average, and standard deviation of 4, 36, and 67 m^2, respectively.

Evidence of lethal entanglements of marine organisms was also found, providing more evidence that ALDFG continues ghost fishing commercial, recreational, and non-target fish species as well as threatens protected wildlife species. Three events (two conglomerates removed from O'ahu and one dFAD from NPG) contained fish bones, including a marlin bill. One abandoned gillnet in Kāneʻohe Bay had killed one juvenile scalloped hammerhead shark (*Sphyrna lewini*), two black tail snappers (*Lutjanus fulvus*), and one big eye scad (*Selar crumenophthalmus*) before rapid removal could happen (within 19 h of discovery). One particularly large conglomerate, which remained on the coral reef in Kāneʻohe Bay for 17 months before removal was possible, contained carapace scutes and plastron bones of one juvenile green sea turtle (*Chelonia mydas*). One distinct net from Laysan in the NWHI contained yellow, white and gray feathers from a bird of unknown species. One dFAD raft on the shoreline of Laysan could not be removed completely because an endangered Hawaiian monk seal (*Neomonachus schauinslandi*) was resting on it, and one distinct net snagged on a coral reef in Kure Atoll had entangled a live monk seal that was released during ALDFG removal. Entanglement of Hawaiian monk seals by ALDFG, especially in the NWHIs, is a common occurrence that threatens this critically endangered species (Boland and Donohue, 2003; Donohue and Foley, 2007). The types of entangling ALDFG documented in this study align with the conclusions of Gilman et al. (2021) that ALDFG from gillnet, tuna purse seine with dFADs, and bottom trawl fisheries have the highest global adverse environmental risks.

ALDFG also causes major economic costs from navigational hazards and removal/disposal operations (McIlgorm et al., 2020). Of the 18 ALDFG events removed by the Hawaiʻi-based longline fishing fleet in this study, 15 of them were snagged on the vessels' propellers or fishing gear. Two of these events caused major engine damage, one of which required the vessel to be towed to port from distant pelagic waters. This is a common, expensive, and dangerous occurrence for this fishing fleet that operates in or near the GPGP (Uhrin et al., 2020). True removal and disposal costs of ALDFG are difficult to estimate because the majority of cleanup operations in the US are performed by volunteers of NGOs that operate on very limited budgets, compared to professional salvage companies or government environmental waste services. This study spent US$241,000 to remove and study 14.7 metric tons of ALDFG. The simple calculation of >US$16,000 per metric ton is not an accurate depiction of removal and disposal costs. On one hand it is an underestimate, because many partner organizations contributed to these removals and their funding is not reflected in this estimate. On the other hand, most of this funding was spent on additional activities, namely researching the amounts, types, polymers, and sources of the ALDFG. The bounty for ALDFG with the longline fishers was highly successful and cost $1 per dry pound (US$2205 per metric ton) for the at-sea removal operation. The cost of storing, transporting, processing, and disposing/recycling of the ALDFG must be additionally considered. These steps are currently provided in-kind by for-profit companies on O'ahu in the Nets-to-Energy program. Without the assistance of these companies, the transportation costs and landfill fees would inhibit NGO removal operations. In that sense, regional fisheries management organizations should consider designing lost gear retrieval plans to reduce, as much as possible, the potential impact caused by ALDFG.

4. Conclusions

To our knowledge, no other ALDFG study rivals the extent and scope of this study, with 253 events recovered and systematically documented from over ≅ 2.5 million km^2. This large amount of ALDFG is impacting the ecology and economy of remote islands of the CNPO. Government agencies in the US are responsible for keeping waters and shorelines clean, but resources are severely limited to remove this level of ALDFG at-sea, on reefs, and even on the shoreline. Due to the threats to marine wildlife and ecosystems, solutions should be prioritized and must include multiple approaches, including research on fishing gear loss, continual removal of the ALDFG, and source prevention. Most of the floating debris identified in this study is from distant fisheries not belonging to Hawaiʻi. Therefore, the solutions require international agreements among regional and national fisheries management organizations, fishing companies, researchers, and NGOs. Commitments to reduce ALDFG, mark fishing gear, innovate fishing gear to use alternative materials, and protect sensitive habitats and species are needed.

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CRediT authorship contribution statement

Sarah-Jeanne Royer: Conceptualization, Data curation, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Raquel N. Corniuk:** Data curation, Methodology, Investigation, Project administration, Visualization, Supervision, Writing – review & editing. **Andrew McWhirter:** Data curation, Methodology, Investigation. **Harry W. Lynch:** Conceptualization, Data curation, Methodology, Investigation, Resources. **Kydd Pollock:** Conceptualization, Data curation, Methodology, Investigation, Writing – review & editing. **Kevin O'Brien:** Funding acquisition, Investigation, Resources, Writing – review & editing. **Lauriane Escalle:** Methodology, Investigation, Writing – review & editing. **Katherine A. Stevens:** Data curation, Investigation, Visualization. **Gala Moreno:** Methodology, Investigation, Resources. **Jennifer M. Lynch:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Investigation, Project administration, Resources, Visualization, Supervision, Writing – original draft, Writing – review & editing.

Data availability

All data are available in the main text or the supplementary materials.

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NIST disclaimer

Certain commercial equipment, instruments, or materials are identified in the present study to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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