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

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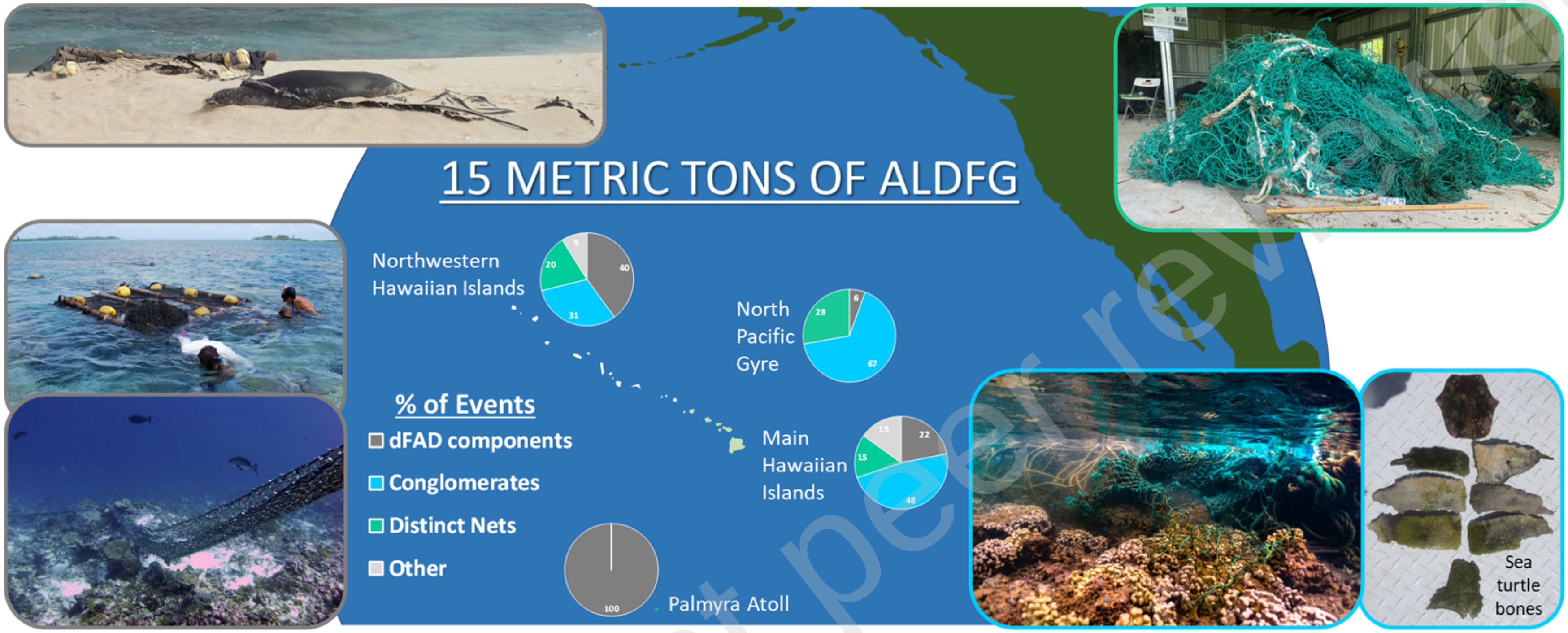
Graphical Abstract



Abstract

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 North Pacific Ocean from 2009-2021. 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 7 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 were reported. The data highlight the large magnitude of ALDFG and associated impacts in the Central North Pacific Ocean.

Keywords: derelict fishing gear; plastic pollution; fish aggregating device; protected species; marine protected areas; ghost fishing

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 Hawaiʻi, 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 significant, but not well documented, percentage of marine debris. Determining accurate rates of fishing gear loss is challenging (Richardson et al., 2021, 2019). As early as 1975, 135,400 tons of plastic fishing gear was estimated to have been dumped into the ocean by global fishing fleets (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 is lost in the ocean annually. The fisheries these authors investigated included industrial trawl, purse seine, and pelagic longline, as well as gillnet, pots, and traps fisheries. The Great Pacific Garbage Patch (GPGP) in the northeastern Pacific Ocean holds the majority of the 96,400 metric tons of floating plastic pollution estimated to be in the 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 greater than 5 cm (Lebreton et al., 2022). The magnitude of this pollution is large.

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, and particular kinds of gear are worse than others (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 toward 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 objects floating in the ocean. Fishers have taken advantage of this behavior by constructing human-made floating objects to harvest fish more easily (Castro et al., 2002). 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). A fish aggregating device (FAD) is a man-made floating object specifically used to aggregate fish. The 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 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 (Lopez et al., 2022). Typically, tropical tuna dFADs are made of a floating bamboo raft (≅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 dark 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 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 toward the Hawaiian Islands, windward reefs and coastlines continually collect debris (Brignac et al., 2019; Miron et al., 2021). Yearly, hundreds of tons of plastic pollution 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 Kaua'i and Hawai'i Wildlife Fund have removed up to 74 metric tons per year from just two Main Hawaiian Islands (MHI) (Berg and Lamson, personal communication). Despite the wide-ranging impacts, ALDFG is underreported and systematic detection surveys are rare in Hawai'i (Moy et al., 2018) and elsewhere. Here, we report the amounts and frequencies of large ALDFG events, including dFADs, washing ashore in the NWHI, MHI, and Palmyra Atoll, as well as recovered from the North Pacific Subtropical Gyre (NPG). This manuscript is the first of four planned from 15 metric tons of ALDFG sampled. Its objective is to provide useful information on the distribution, types, and magnitude of ALDFG events in the North Pacific Ocean. Future manuscripts will describe the plastic polymer composition of the distinct gear types found (Corniuk et al. in review), compare the gear types found in conglomerates across three different study regions (McWhirter 2022), and reveal source fisheries and gear manufacturers or countries to the best of our ability (Lynch et al., in prep). 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 North Central Pacific Ocean.

2. Methods

2.1 Study regions

The remote Hawaiian archipelago in the Central North Pacific Ocean 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 located in the PMNM and are uninhabited except for a small number of conservation and research personnel. The MHI host over 1.4 million residents and 8 million visitors per year. Palmyra Atoll (PAL) is located 1,600 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 (Figure 1). A large ALDFG event is defined here 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 (max in this study was 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 four 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 (section 2.2) of the study, so comparing ALDFG quantities across regions or time is not possible with these collection campaigns.

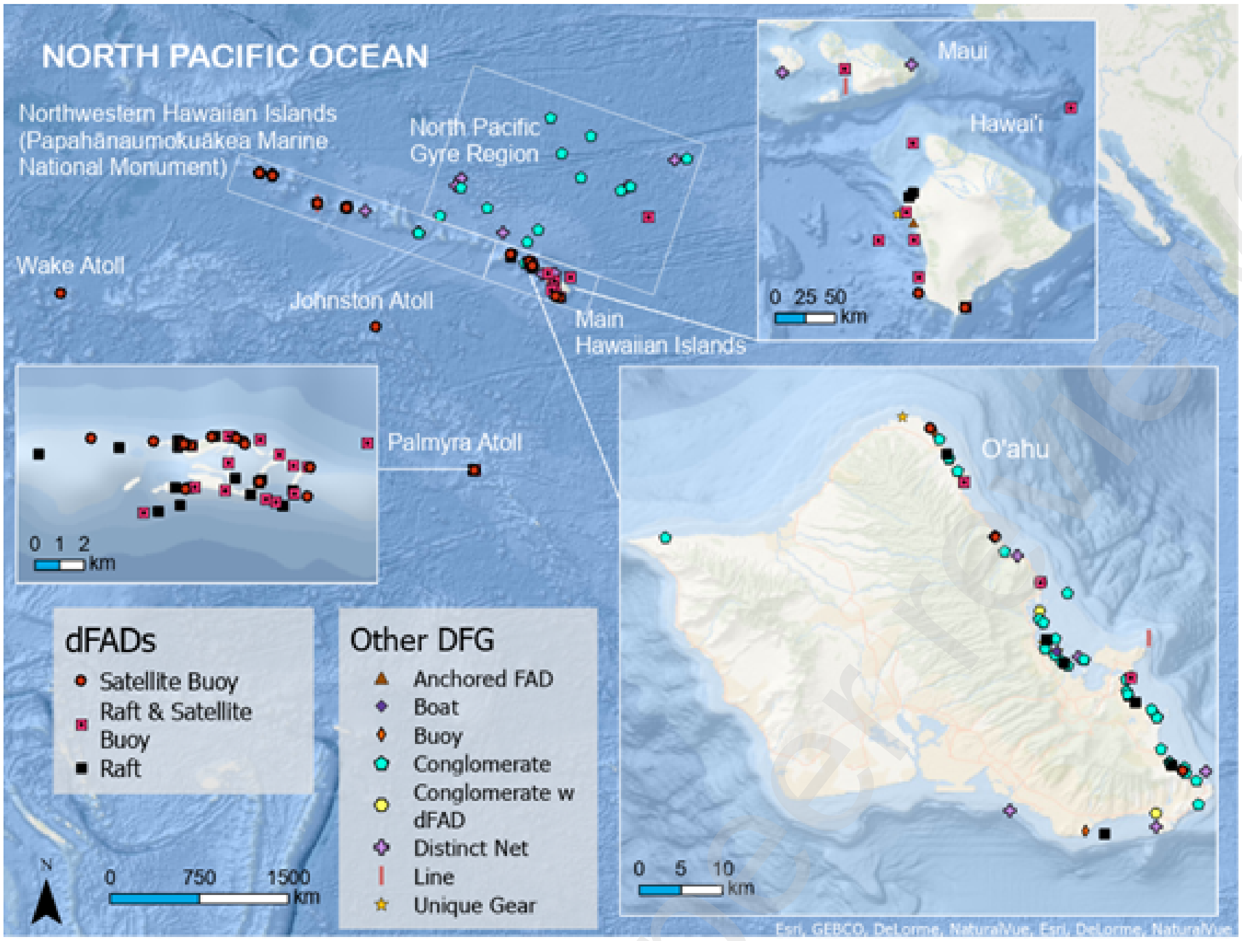


Figure 1: Map of ALDFG events that had location coordinates and were recovered as marine debris from 2009 to 2021 in the main Hawaiian Islands, Papahānaumokuākea Marine National Monument, North Pacific Gyre Region, and Palmyra Atoll.

Table 1. Methods for detecting and documenting ALDFG in four 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	>100s people

	all large ALDFG	2019-2021	public reports; cleanup missions of many organizations	>100s 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

2.2.1 Palmyra Atoll (PAL)

The Nature Conservancy and the U.S. Fish and Wildlife Service (FWS) began documenting dFAD strandings at Palmyra Atoll 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 of 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 general public reported the detection of ALDFG through social media, hotlines monitored by non-governmental organizations (NGOs), and an online form created by the Hawai‘i 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 (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 nearshore reefs. ALDFG events from two missions, October 2020 and April 2021, were selected with the following criteria. From the 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 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, the following information was recorded a database: event ID, date and GPS location of the encounter, region, date removed, ALDFG type, habitat type, presence and description of entanglement of wildlife, damage to habitat, ALDFG dimensions, dry mass, removal organization, and disposal mechanism. ALDFG types were categorized as conglomerates, distinct nets, distinct lines, buoys not related to dFADs, unique gear, and dFAD components (Figure 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.

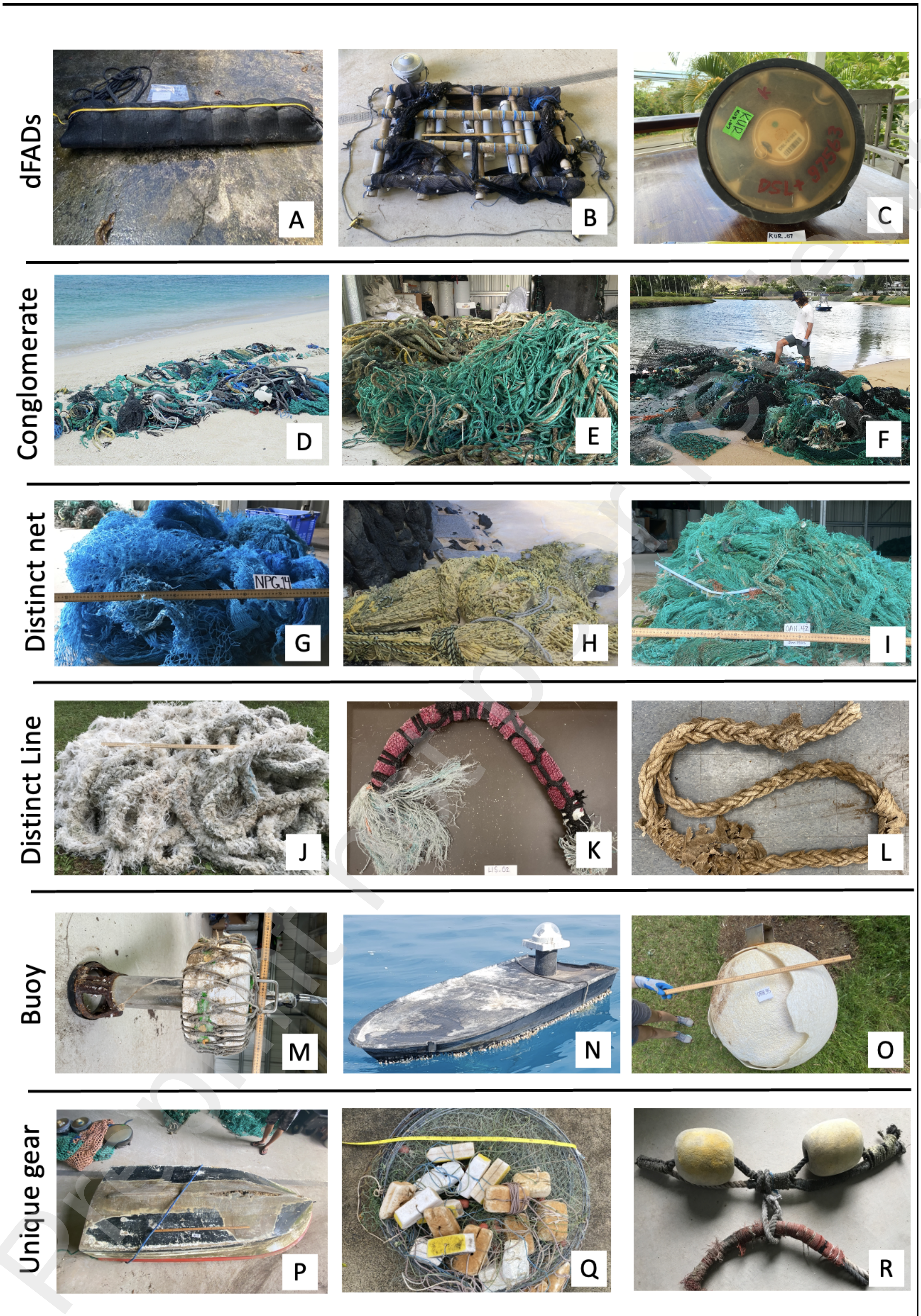

dFADs
A
B
C
Conglomerate
D
E
F
Distinct net
NPG.14
G
H
I
Distinct Line
J
K
L
Buoy
M
N
O
Unique gear
P
Q
R

Figure 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.

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. ALDFG presence was recorded regardless if the debris were small items (approximately 1 cm or larger), such as monofilament fishing line, lead weights, metal hooks, lures, small floats, oyster spacers, and eel trap entrances or large items, like dFAD rafts and conglomerates (max was a 4.5-m long conglomerate). This surveillance effort was opportunistic. However, visual (above water) surveys were performed of the shallow fringing and patch reefs in Kāneʻohe Bay on the island of Oʻahu from a 19-foot Boston Whaler at least monthly specifically for this project. The survey route was documented but was not standardized across the study. Thus, the documented surveillance effort was unevenly distributed across island sides and from the shore versus on the water surveys (Table 3). Most effort took place on the east side of Oʻahu. Data recorded during each survey included the date, start and stop time, shore vs. boat survey, participant names, island, island side, area transited, above or below water visual method, whether marine debris was observed, whether ALDFG was observed, whether the debris was removed, whether ALDFG was a large event added to the ALDFG database, debris description, debris count removed, debris mass removed, and debris disposal method. The total quantity of marine debris removed per total number of survey days was calculated to act as a proxy for quantities of plastic pollution commonly recovered from these locations during the two-year time period. In this surveillance dataset, all types of marine debris, according to the NOAA Marine Debris Program definition (NOAA Marine Debris Program, 2021b), were removed and cumulatively weighed each day. The debris was not only plastic and not only ALDFG.

Table 3. Summary of marine debris surveillance effort and results in the Main Hawaiian Islands. Gray rows indicate tenuous data because these island sides were surveyed for only five or fewer days.

Island	Side of island	Days surveyed	Hours surveyed	Days surveyed from shore	Days surveyed on water	kg of debris removed	% of days debris observed	% of days ALDFG observed	kg debris removed/ day
Oʻahu	N	2	11	1	1	15.8	50	50	7.9
Oʻahu	NE	11	30.75	10	1	62.8	100	91	5.7

O‘ahu	E	85	220.07	37	48	1579	74	56	18.6
O‘ahu	SE	8	35.5	1	7	0.7	38	25	0.09
O‘ahu	S	9	23.7	5	4	2.5	89	44	0.3
O‘ahu	W	5	25.35	2	3	1.5	80	20	0.3
Maui	NW	1	1.5	1	0	not measured	100	100	not measured
Maui	N	4	2.78	4	0	0	0	0	0.0
Maui	E	3	3	3	0	5.6	67	67	1.9
Maui	S	9	24.3	5	4	7.7	56	22	0.9
Maui	SW	11	33.05	10	1	2.3	91	55	0.2
Maui	W	2	5.5	2	0	0.6	100	100	0.3
Molokai	W	1	8.5	0	1	0	0	0	0
Lāna‘i	N	9		0	9	not measured	100	100	not measured
Hawai‘i	W	1	2	1	0	0	0	0	0.0
All Locations		26	74.35	20	6	16.1	74	55	10.4

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 (Figure 1), totaling ≅15 metric tons. The event level data are provided in Table S1. The majority of the events were dFAD components (151 individual dFAD events and 2 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. They were added to the database nonetheless. Conglomerates were the second dominant event type (61 including two containing dFAD parts). Distinct nets were the third (25 events). Less common event types were five buoys not related to dFADs (including two anchored FADs), four distinct lines, and seven unique gear events. 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 4). The average ALDFG event weighed 98.7 kg. 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 together by people, perhaps for makeshift FADs, or they tangle in the ocean upon encountering each other. We believe the latter is more likely because we observe haphazard twists, lines that are snaked through other gear in complicated ways (like tangled necklaces), 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 Hawai‘i Marine Debris Action Plan have found and removed this type of marine debris for decades (NOAA Marine Debris Program, 2021a). More information regarding the polymer composition and sources of these ALDFG events will be included in future publications, but brief preliminary findings will be explained here. Most of the ALDFG is composed of polyethylene and polypropylene, which are floating polymers. 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 Hawai‘i. Since the gear floats, it drifts from faraway places to these remote island regions. Notably, the detection of this ALDFG is not a full picture of all ALDFG in the Central North Pacific Ocean 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 Hawai‘i, should receive attention in future studies.

Table 4. Mass and volume of large ALDFG events removed from the Central North Pacific Ocean.

		Mass (kg)							Volume (m^3)				
ALDFG Event Type	n	Total	Average	SD	Min	Max		n	Total	Average	SD	Min	Max
Conglomerate	61	10387	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	14703	98.7		0.15	19.9		76	141	1.9		0.06	5.4

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 (Figure 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 the authors. For this reason, the largest number of ALDFG 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 (Figure 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 Figure 1 because of lesser effort on these islands.

ALDFG event types differed across regions (Figure 3a), but this comparison is also biased by different levels of effort and 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 (Figure 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 in NPG because of the small sample. The PAL events were exclusively dFAD components, whereas dFAD events made up only 22 % of the MHI and 6 % of the NPG events (Figure 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 (Figure 3b), but this was a result of event selection that was biased towards dFADs. From our experience, dFADs do not represent 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).

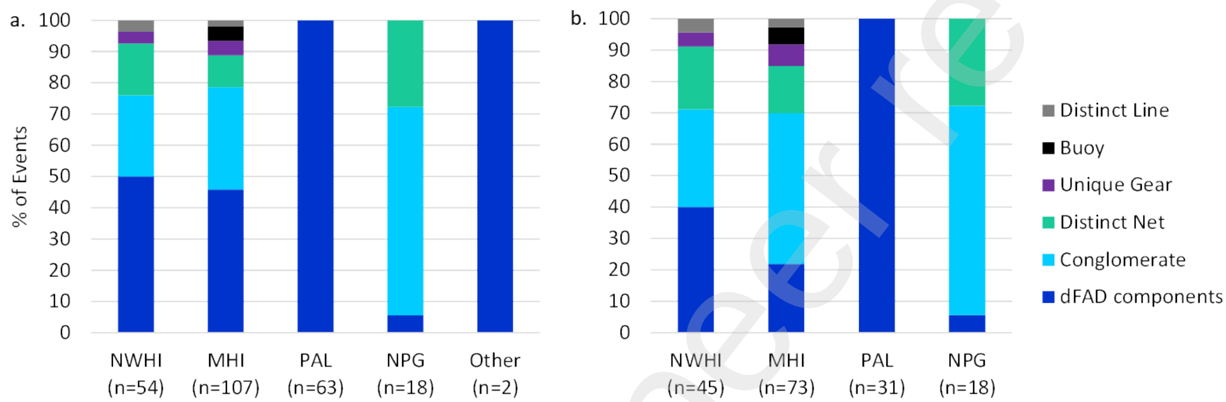


Figure 3. ALDFG event types documented in the regions of the North Central Pacific Ocean a) within the entire database and b) standardized to only events found between Oct 2019 to Dec 2021. Regions include the Northwestern Hawaiian Islands (NWHI), Main Hawaiian Islands (MHI), Palmyra Atoll (PAL), North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

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 (Figure 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. Very few dFADs still contained tails. Where the tails and other parts were lost is often unknown. 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.

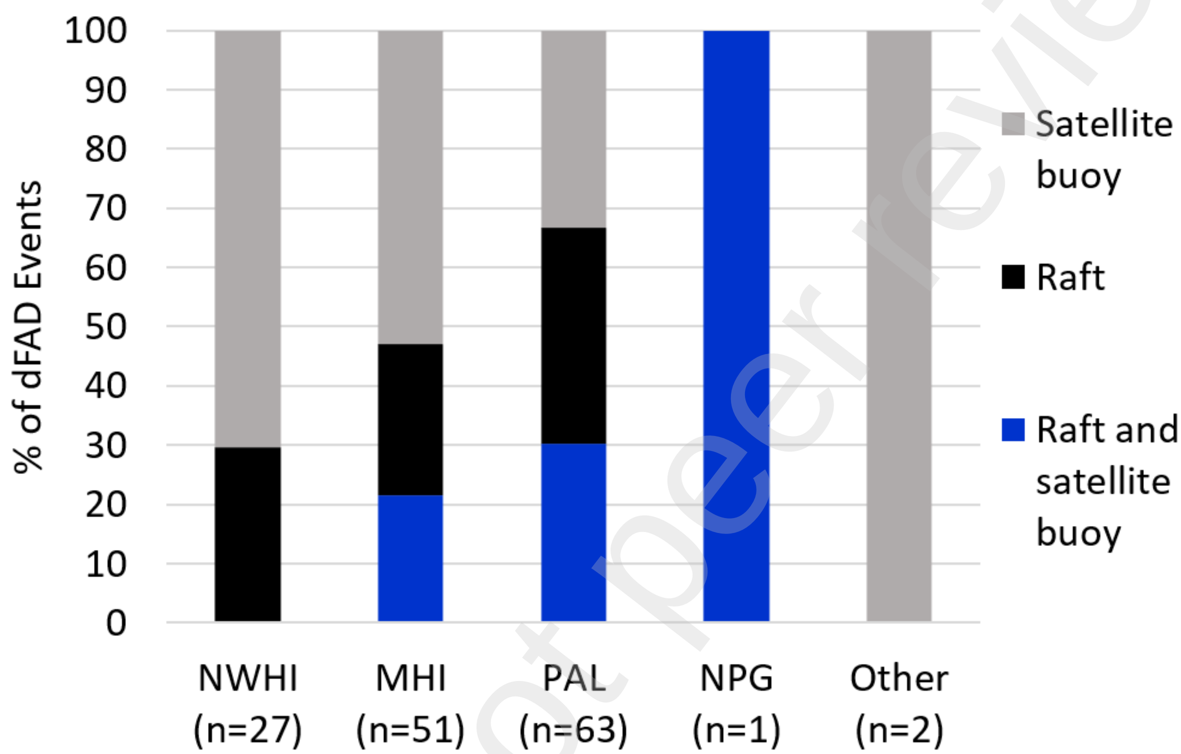


Figure 4. Percentage of dFAD events found as marine debris in the Central North Pacific Ocean with the raft still connected to the satellite buoy compared to those found as an individual separated part. Regions include the Northwestern Hawaiian Islands (NWHI), Main Hawaiian Islands (MHI), Palmyra Atoll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

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

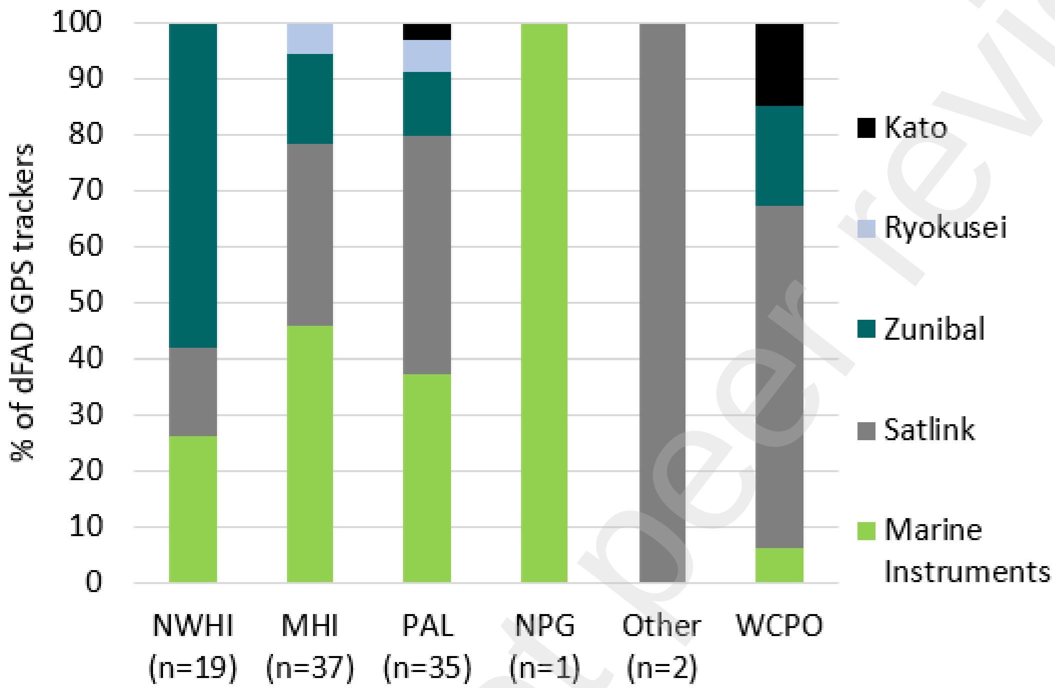
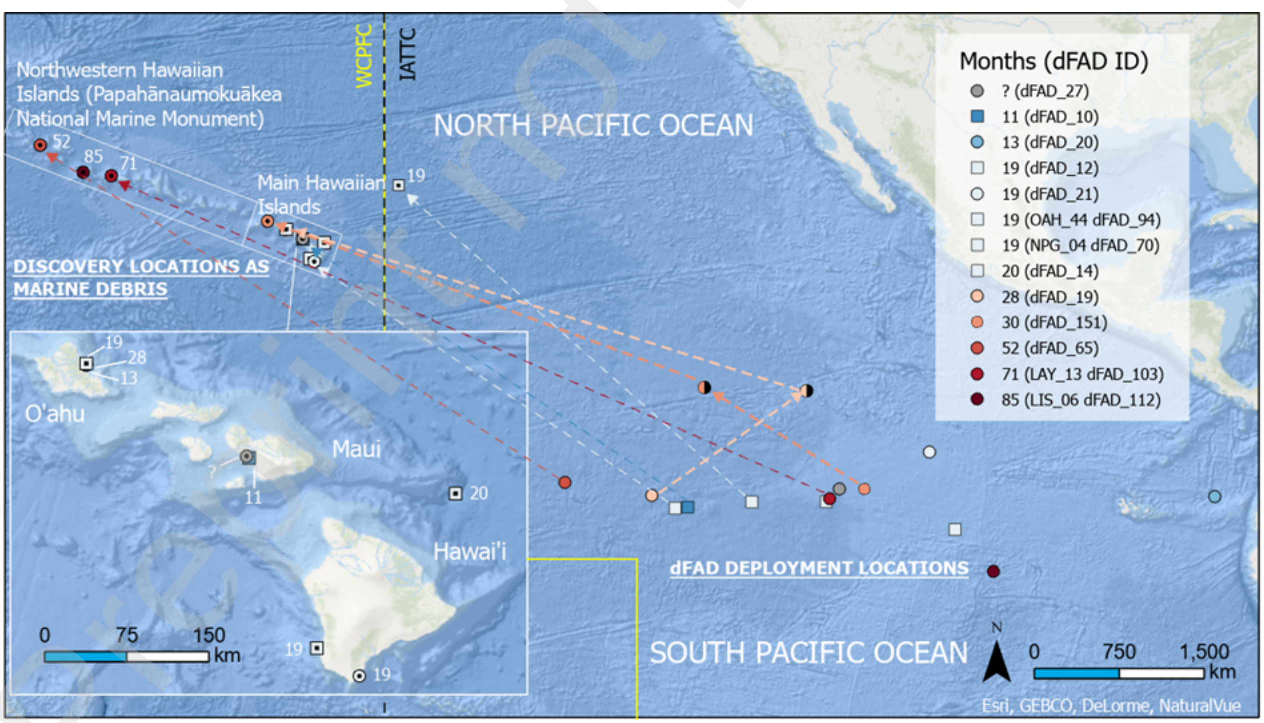


Figure 5: Percentage of manufacturers of dFAD satellite buoys found as marine debris in the Central North Pacific Ocean. Regions include the Northwestern Hawaiian Islands (NWHI), Main Hawaiian Islands (MHI), Palmyra Atoll (PAL), North Pacific Gyre region (NPG), and two events from Wake and Johnston Atolls (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.

DFAD buoy IDs were searched through a Marine Instrument database for deployment information. Of the 30 dFAD satellite buoys searched, deployment year and months were found for 24 (80.0 %) and deployment locations were revealed for 23 (76.7 %) buoys (Table S1). All search results showed deployment locations within the Eastern Pacific Ocean (EPO, Figure 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 Hawaii with the EPO than the WCPO (Escalle et al. 2022c).

Months between deployment and discovery/removal as marine debris ranged from <3 months to 85 months (Table S1; Figure 6). Most dFADs arrived in the MHI and PAL less than 2 y after deployment (Figure 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 degrees of freedom, $p < 0.0001$; Figure 7a). The deployment latitudes of the identified dFADs ranged from 4.3 °N to 17.3 °S (Figures 6 and 7b), and longitudes ranged from 73.4 °W to 149.7 °W (Figure 7c). The original deployment latitudes or longitudes of dFADs did not differ significantly among the four arrival regions (Wilcoxon or ANOVA, respectivly, $p < 0.05$).

a.



b.

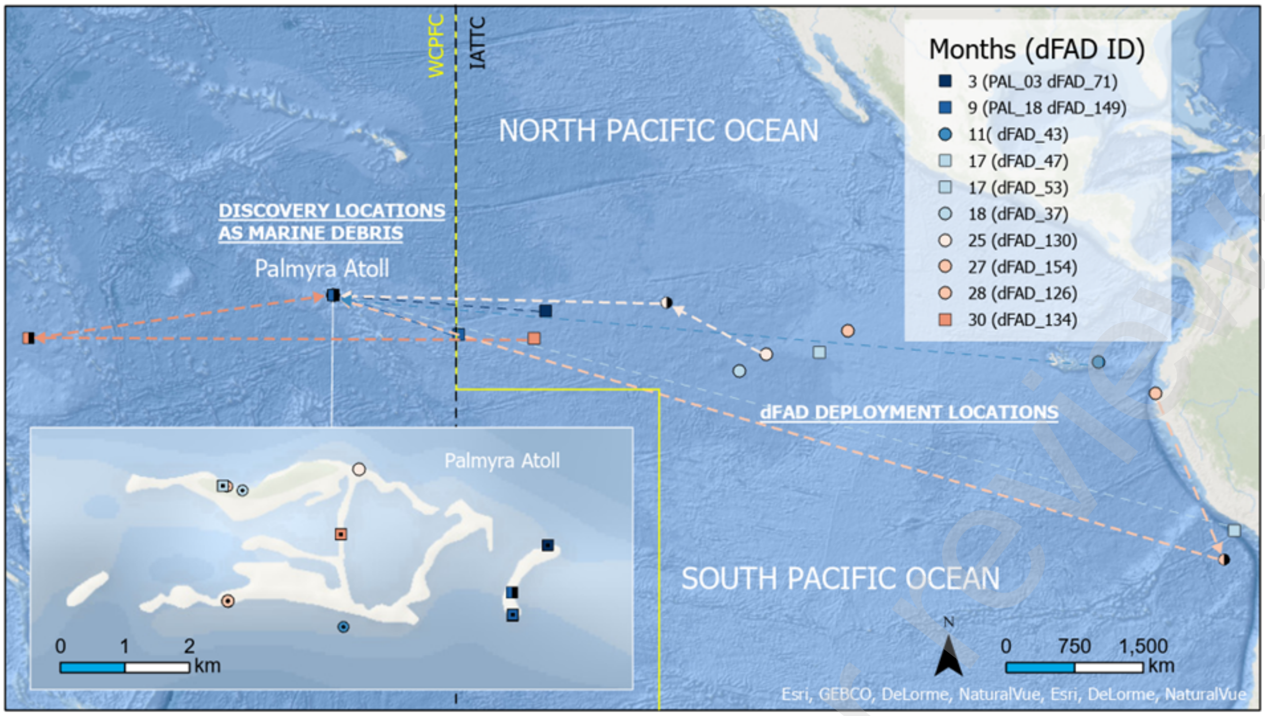
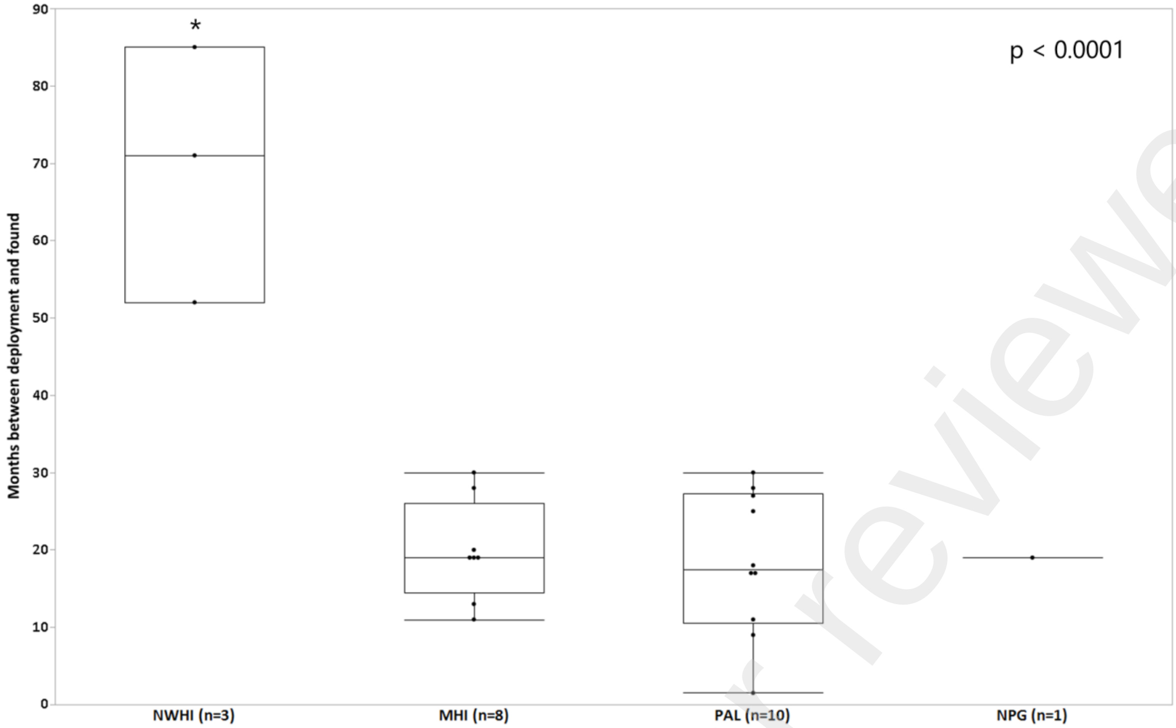


Figure 6. Locations of individual dFADs from deployment to discovery as marine debris in a) the Hawaiian Islands and b) Palmyra Atoll. The colors depict the duration between deployment and discovery in months with blues as the shortest and reds as the longest. Squares indicate dFAD rafts still attached 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.

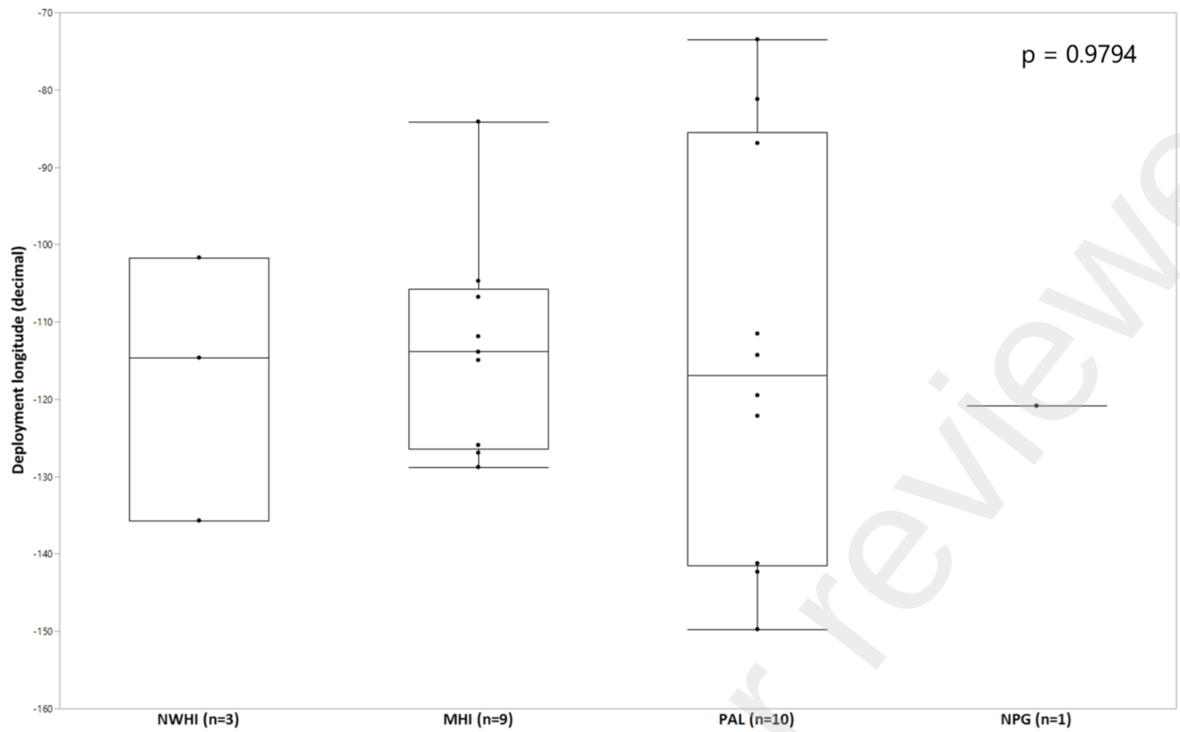


Months between deployment and found
p < 0.0001
*
NWHI (n=3)
MHI (n=8)
PAL (n=10)
NPG (n=1)

a.

Deployment latitude (decimal)
p = 0.9442
NWHI (n=3)
MHI (n=9)
PAL (n=10)
NPG (n=1)

b.



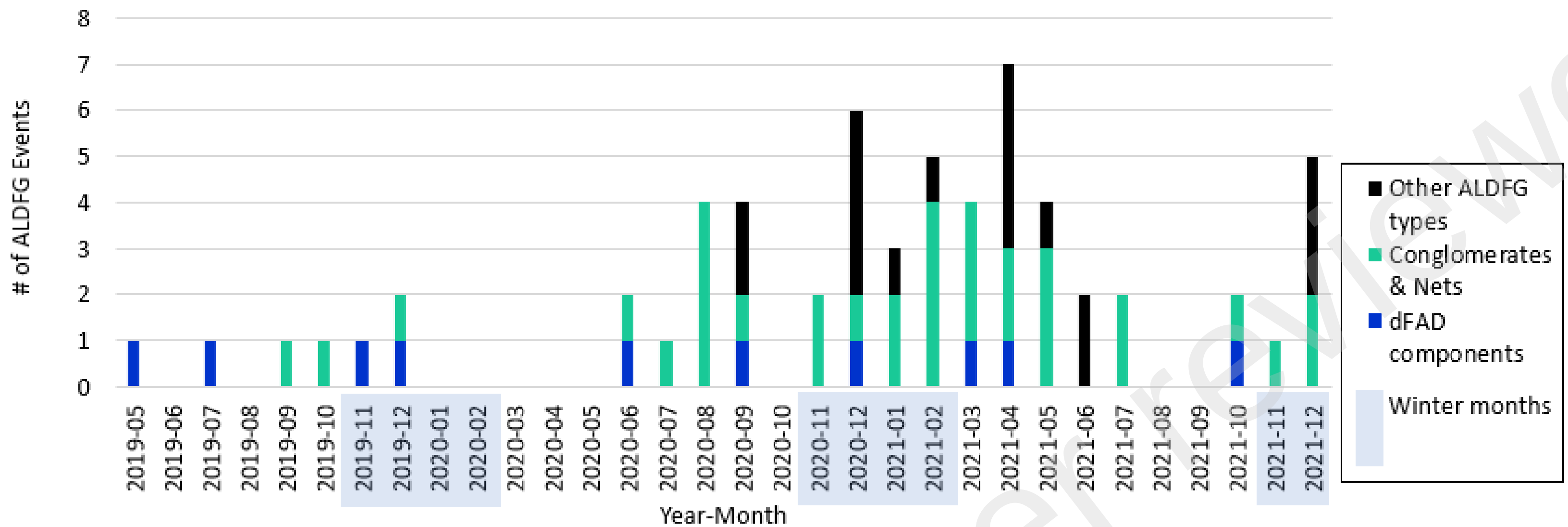
c.

Figure 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).

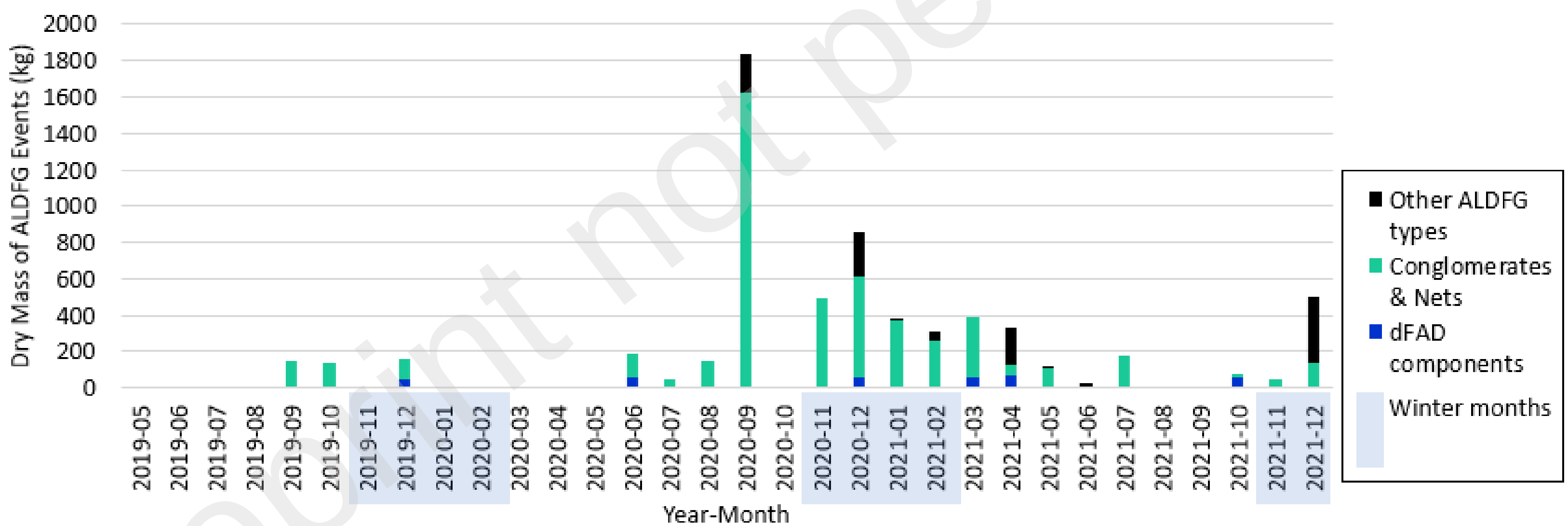
Significant data gaps exist in the distribution and frequency of lost dFADs. Many options are available (not without challenges) to reduce losses of dFADs and impacts of these losses. With tens of thousands of dFADs deployed each year (Gershman et al., 2015), even low rates of gear loss can result in large numbers of lost FADs globally (Maufroy et al., 2015). Remote islands in the North Pacific Ocean 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, 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 (Figure 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 (Figure 8b) with a peak in September 2020 due to a single 1614-kg conglomerate. The second highest month was December 2020, in 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 (Figure 8).



a.



b.

Figure 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.

3.5 ALDFG surveillance results in MHI

During 161 days of documented surveillance efforts in the MHI, more than 1600 kg of marine debris were removed, mostly from the east side of Oʻahu (Table 2). Island sides with less than six survey days are not discussed. Marine debris was detected from 38 % to 100 % of survey days, depending upon the island side, and ALDFG (of all types and sizes) was detected between 22 % and 100 % of days depending on island side (Table 2, Figure 9). The mass of marine debris removed per day was greatest on the east side of Oʻahu at 18.6 kg/day, followed by Oʻahu's northeast side. The presence of ALDFG was frequent on both the windward (east) and leeward (west) sides of Oʻahu and Maui, but the windward sides had greater quantities of marine debris (Figure 9).

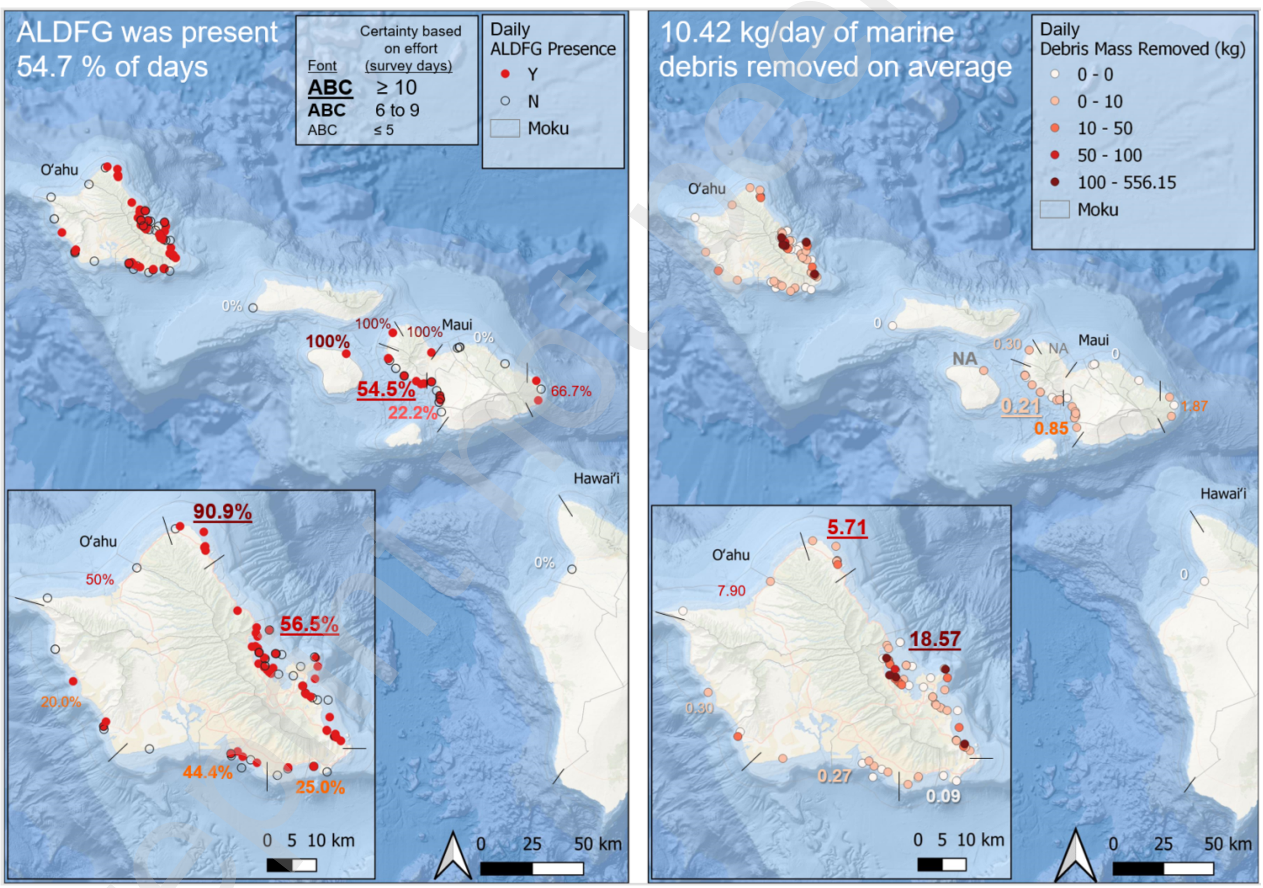


Figure 9. Map of surveillance results for marine debris and ALDFG on five Main Hawaiian Islands. Markers on the map indicate a day of surveillance. Gray lines border the mokus, or Hawaiian traditional land management areas from mountain ridge to reef. Black lines indicate transitions between different 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 each side of each island, as the average mass of marine debris removed per survey day.

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 Hawai'i and the east shores of Kaua'i (Brignac et al., 2019). This preliminary exercise is the first to provide ALDFG quantities per unit effort in Hawai'i. Normalizing to effort allows for better geographic comparisons and an understanding of the magnitude and frequency of this pollution. ALDFG is fairly omnipresent across the MHI shown by the moderate to high frequency of occurrence, but the quantities of marine debris are strikingly different between sides of the same island (Table 2, Figure 9). The windward (east) sides are known to receive large amounts of floating plastic debris that do not originate from Hawai'i. Instead, debris is thought to come from the GPGP and is caught by the islands' windward shorelines (Brignac et al., 2019; Maximenko et al., 2018; Miron et al., 2021; Ribic et al., 2012). In contrast, the leeward (west) sides are more protected from this source of pollution but receive smaller amounts of debris from people in Hawai'i (Brignac et al 2019). Recreational hook and line fishing is widespread throughout the Hawaiian Islands (Wedding et al., 2018), resulting in locally-sourced ALDFG being omnipresent. This type of gear is typically made of nylon monofilament line that sinks in seawater and is often attached to metal weights, resulting in the gear sinking where it was lost. In contrast, very large conglomerates of lost ropes and nets 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. Because of these different sources and types of ALDFG, the quantities available for removal on the windward sides (e.g. 18.6 kg/day on East O‘ahu) are much greater than on the leeward sides (e.g. 0.3 kg/day on South O‘ahu). The vast differences in ALDFG types removed from windward versus leeward sides are shown in representative photos (Figure S1).

3.6 ALDFG ecological and economic impacts observed

This study focused on floating ALDFG, most of which does not originate from fisheries in Hawai‘i, but harms the coral reef habitats surrounding the Hawaiian Islands and Palmyra Atoll. Fourteen percent of the events were snagged on coral reefs (Figure 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 toward 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 Hawai‘i-based longline fishing fleet was paid a bounty to remove and bring back ALDFG from their distant, pelagic fishing grounds.

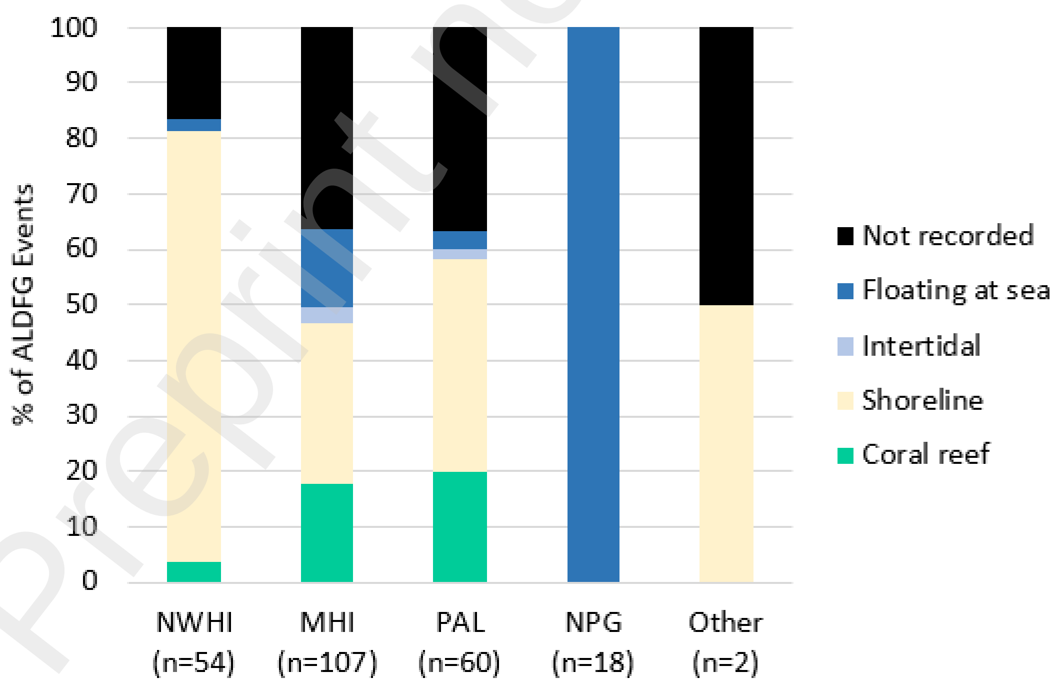


Figure 10. Percentage of environments where ALDFG was found as marine debris in the Central North Pacific Ocean. Regions include the Northwestern Hawaiian Islands (NWHI), Main Hawaiian Islands (MHI), Palmyra Atoll (PAL), North Pacific Gyre (NPG), and two events from Wake and Johnston Atolls (Other).

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.

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 Kāne‘ohe 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 Kāne‘ohe 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 Hawai‘i-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$2,205 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 Central North Pacific. 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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Acknowledgments

This work was supported by the Norwegian Retailers' Environment Fund [grant number 3-185]. We thank staff and hundreds of volunteers of our organizations that assisted with ALDFG detection, removals, measurements, transportation, and data entry. Many staff and volunteers of the following organizations provided valuable ALDFG detection, removal, and/or sample/data sharing efforts: Papahānaumokuākea Marine Debris Project, U.S. Fish and Wildlife Service, SHARKastics, Sustainable Coastlines Hawaii, the Hawaii Humpback Whale National Marine Sanctuary, Hawaii Wildlife Fund, Surfrider Foundation, Ocean Voyages Institute, Hawaii Department of Land and Natural Resources (DLNR) Division of Boating and Ocean Recreation (DOBOR) and Division of Aquatic Resources (DAR), Seed, 4ocean, Hawaii Marine Animal Response, Malama Maui Nui, and Ocean Defenders Alliance. We thank Schnitzer Steel, POP Marine, and Covanta for their in-kind services towards disposal of most of the ALDFG in the Nets-to-Energy program.

Author contributions:

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Competing interests: The authors declare no competing interests.

Data and materials availability: All data are available in the main text or the supplementary materials.

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Supplementary Materials

Table S1: Details of each ALDFG event collected between 2009 and 2021 for the main Hawaiian Islands (MHI), Northwestern Hawaiian Islands (NWHI), North Pacific Subtropical Gyre (NPG), and Palmyra Atoll (PAL). Information includes type of ALDFG event (e.g. dFAD, conglomerate), dates, locations, habitat type, entanglement of animals, dimensions, mass, among other data. https://docs.google.com/spreadsheets/d/1_LZhv9PV2c23O1_bJ8yHCNCkOA-ePVLiXS7Yx0MFAHY/edit#gid=0

Figure S1: Representative types of marine debris found on A) windward vs. B) leeward sides of O‘ahu, Hawai‘i. Abandoned, derelict, lost fishing gear (ALDFG) is circled in orange.