Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Decadal debris records reveal legacy accumulation and emerging fishing-derived plastic inputs across the North Pacific

Sarah-Jeanne Royer

sarah-jeanne.royer@theoceancleanup.com

The Ocean Cleanup

Wouter Jan Strietman

Wageningen University & Research https://orcid.org/0000-0002-4637-5786

Peter Puskic

The Ocean Cleanup

Matthias Egger

The Ocean Cleanup

Rafael Bergstrom

Sustainable Coastlines Hawai□i

Kevin O'Brien

Papahānaumokuākea Marine Debris Project

Laurent Lebreton

The Ocean Cleanup

Article

Keywords:

Posted Date: June 28th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10023966/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: There is **NO** Competing Interest.

Abstract

Marine plastic pollution represents one of the most persistent environmental challenges of our time, yet the relative contributions of land- versus sea-based sources remain contested. Here we present a decade-long dataset (2015–2025) comprising over 55,893 kg and 272,638 items of floating debris collected across three regions: the North Pacific Garbage Patch (NPGP), the Papahānaumokuākea National Marine Sanctuary, and the Main Hawaiian Islands. Fishing-related gear dominated debris mass across all regions (~ 71%), with fishing gear fibers comprising the largest fraction by weight. Provenance analysis of 19,768 individually examined items points predominantly to East Asian origin, with Japanese-labelled fishing gear dominating the NPGP as a legacy signal, Chinese-labelled items dominating Hawaiian shorelines consistent with recent fleet expansion, and the near-absence of PET bottles in the NPGP reflecting their high buoyancy, elevated windage, and shorter material lifespan relative to durable polyolefins. Critically, analysis of 174 assessed fishing nets indicates that all were identified as sections of larger nets, of which 87% showed characteristics most consistent with inadequate fishing gear waste management rather than accidental loss, suggesting that routine repair and replacement operations are a key pathway by which floating fishing net fragments reach the open ocean. These findings underscore the urgency of targeting sea-based sources, particularly fishing fleet waste management practices both at sea and in port, in international plastic pollution mitigation strategies.

Introduction

Plastic pollution has emerged as one of the most persistent anthropogenic stressors affecting the world's ocean, with global production projected to double within the next two decades (UNEP, 2022). The composition, buoyancy, and durability of plastic materials strongly influence their transport and fate in the marine environment. Coastal and riverine systems tend to trap denser, more degradable polymers nearshore (Kühn et al., 2015; Lebreton et al., 2017; Meijer et al., 2021; van Emmerik et al., 2018; Weinstein et al., 2016), whereas subtropical gyres and remote islands consistently accumulate buoyant, long-lasting polymers such as polyethylene (PE) and polypropylene (PP) capable of traversing entire ocean basins over decades (Andrady, 2011; Lebreton et al., 2022; Reisser et al., 2014). Among items recovered from gyre environments are "legacy plastics", produced decades ago yet still circulating, with residence times modulated by photodegradation, biofouling, and submesoscale oceanographic processes (Chamas et al., 2020; Lebreton et al., 2019).

The long-standing assertion that approximately 80% of marine debris originates from land-based sources derives from a broad 1990 GESAMP estimate and lacks rigorous empirical support (GESAMP, 1990; Hudson et al., 2025). Recent reassessments, therefore, challenge the assumption that land-based inputs exceed sea-based sources, particularly for buoyant and persistent plastics. For example, Kaandorp et al., (2023) demonstrate that the global floating plastic mass is dominated by large, long-lived items, and suggest that ocean-based activities are likely major sources of this persistent debris. It is important to note, however, that debris composition reflects local conditions and proximity to waste sources: in regions with significant fishing activity, fishing gear can account for 50–100% of recovered

debris (Apete et al., 2024; Richardson et al., 2021), whereas areas in proximity to large urban centres tend to show a greater proportion of land-based consumer waste. In line with this, Saliba et al. (2022) point out that industrial fishing fleets, commercial shipping, and at-sea crew operations contribute to plastics through accidental loss, operational leakage, and illegal disposal (Saliba et al., 2022). Alongside such operational and accidental releases, container spill events alone can introduce pulses of intact, newly manufactured consumer goods into open-ocean circulation, with debris directly linked to remote beach deposits (Molina-padrón et al., 2024, Turner et al., 2021).

Among sea-based inputs, abandoned, lost, or discarded fishing gear (ALDFG), including nets, lines, ropes, buoys, crates, and fish-aggregating device components, is of particular concern, with fishing gear fibers (nets, lines, and ropes) estimated to account for approximately 46% of floating mass in the North Pacific Garbage Patch (NPGP), rising to 76–85% when all ALDFG hard plastics are included (Lebreton et al., 2022, 2018). However, the pathways through which this gear enters the ocean remain poorly characterised, thus limiting the implementation of effective mitigation efforts. Remote offshore islands situated within or downstream of subtropical gyre systems are increasingly recognised as major accumulation sites for long-range drifting debris, making them valuable sentinels for understanding plastic sources, transport pathways, and residence times (Dijkstra, 2025; Lavers and Bond, 2017). To complement offshore gyre observations and situated downstream of the NPGP along major current pathways, the Papahānaumokuākea National Marine Sanctuary (PNMS) and the Main Hawaiian Islands (MHI) serve as critical interception points for long-range debris and provide a complementary perspective to offshore gyre sampling (NOAA Marine Debris Program, 2021, Royer et al., 2023).

Here we present the most comprehensive provenance analysis of North Pacific floating debris to date, using a decade-long dataset (2015–2025) of over 55,893 kg and 272,638 items collected across the NPGP, PNMS, and MHI. Through systematic classification of 19,768 individually marked items and forensic analysis of a sub-sample of 181 net fragments, we characterise debris composition, geographic origin, time at sea, and critically the pathways by which fishing gear enters the ocean, with the aim of strengthening the empirical foundation for targeted, source-specific mitigation policy.

Results

Overview of debris mass, count, composition, and fishing gear contribution across six North Pacific collection sites

Plastic marine debris was collected across three regions of the North Pacific and six locations spanning thousands of kilometres: the NPGP, the PNMS, and the MHI (Fig. 1). The NPGP represents the most offshore site within the subtropical gyre circulation, the PNMS comprises remote Northwestern Hawaiian Islands positioned downstream of the NPGP, and the MHI represents nearshore island environments more strongly influenced by regional oceanographic processes (Fig. 1A–B). Across 92 cleanup events spanning 2015–2025, a total of 55,893 kg and 272,638 items greater than 5 cm were collected (Fig. 1C; Table 1).

Fishing-related gear dominated the debris mass budget across all three regions, comprising 71% of total collected weight (Fig. 2A). This dominance was most pronounced in the NPGP (85%), where two categories together accounted for the vast majority of recovered mass: fishing-gear fibers, nets, lines, and ropes, at 64%, and fishing-gear hard plastics, including floats, buoys, crates, eel traps, and oyster spacers, at 21%. Fishing gear contributions were also substantial in the PNMS, ranging from 61% at Kuaihelani/Pihemanu (Midway Atoll) to 78% at Kapou/Papa□āpoho (Lisianski) Island, and in the MHI, where fishing gear comprised 72% at Kalaupapa and 58% at Kahuku. Within all regions, fishing gear fibers represented the single largest weight category, totalling 37% of combined mass, while fishing-gear hard plastics contributed a further 34%.

Weight- and abundance-based distributions provided complementary but contrasting views of debris composition (Fig. 2). By weight, the NPGP contributed the highest overall mass (24,959 kg), dominated by fishing-gear fibers (62%), followed by household items (8%), crates (8%), and floats/buoys (8%). The PNMS (22,136 kg total) showed similarly high fiber contributions (36%), alongside substantial floats/buoys (28%) and household items (15%). The MHI (8,743 kg total) had a lower total mass but a higher relative contribution of floats/buoys (28%) and fragments greater than 5 cm (9%; Fig. 2A). By item count, the picture shifted markedly: fragments greater than 5 cm (34%), aquaculture gear (14%), and food and drink items (14%) dominated numerically across all regions, reflecting the prevalence of small, fragmented, and consumer good items. MHI, despite contributing the lowest proportion of total mass, exhibited the highest item counts with 91,808 items (45% of the combined total), a pattern that partly reflects differences in collection methods across regions, shoreline cleanups at MHI allow recovery of small items that are not retained by offshore collection systems in the NPGP or prioritised during large-scale island cleanups for PNMS, demonstrating that a small number of heavy categories drive the mass budget, while numerous small items dominate counts, underscoring the importance of analysing both metrics jointly (Fig. 2B).

Hard plastic debris: composition, provenance, and age

A total of 19,768 hard plastic items bearing identifiable source markers were examined individually across the three regions, including language markings, manufacturing stamps, and production and expiration dates (Fig. 3–6). Floats and buoys were the most frequently recorded item type with identifiable source markers (7,019 items; 36%), driven by exceptionally high abundance in the PNMS, with additional contributions from the MHI and NPGP (Fig. S1). Drink bottles and containers formed the second-largest category (2,824 items; 14%), dominated by PET bottles (75%), and concentrated in the PNMS and MHI, with very few in the NPGP (5%). Caps and lids (2,813 items; 14%), other bottles and containers (1,200 items; 6%), cleaner bottles (922 items; 5%), and jerry cans (704 items; 4%) were also widely represented. Industrial items, including crates (704 items; 4%) and engine oil containers (466 items; 2%), were most abundant in the NPGP (Fig. S1).

Production countries, written languages, and brands.

The country of an item's production was identified on 6,970 items, with China the predominant source (3,769 items; 54%), followed by Japan (1,479 items; 21%), South Korea (385 items; 6%), Indonesia (330 items; 5%), and the United States (291 items; 4%; Fig. 3A). Written-language markings on 15,402 items mirrored this pattern, with Chinese the most frequently observed language (7,433 items; 48%), followed by Japanese (2,893 items; 19%), English (2,618 items; 17%), and Korean (1,377 items; 9%; Fig. 3B). Regional signatures diverged notably by debris type (Fig.4): in the NPGP, Japanese was the dominant language on ALDFG hard plastics, particularly floats, buoys, and crates, while Chinese dominated ALDFG items in the PNMS, and a mixed Chinese and Japanese characterised the MHI. In contrast, consumer items across all regions were overwhelmingly Chinese-labelled, especially PET drink bottles, caps, and cleaner containers. This decoupling between the dominant language of fishing gear versus consumer packaging provides new insight into the distinct source sectors and transport pathways contributing to debris in each region (Fig. 4). Brand markings identified on 11,327 items across 2,594 distinct brands further reinforced these geographic patterns, with Chinese float and buoy manufacturers, including Zhejiang, Yufa, and Sun Brand, and Chinese beverage brands dominating overall, while Japanese float manufacturers such as Sanshin Kako and Nichimo were disproportionately represented in the NPGP (Fig. 5A). International brands including Nestlé, Coca-Cola, and Aqua were present across all regions but at considerably lower frequencies than regional Asian brands. The geographic distribution of production countries across the broader Pacific Rim confirms the dominance of East Asian sources across all tiers of the provenance dataset, with contributions from Southeast Asian, North American, and Latin American nations forming a secondary signal consistent with North Pacific circulation pathways (Fig. 5B).

Production and expiration dates.

Production dates were identified on 1,138 items spanning more than six decades, from 1960 to 2025, with a pronounced increase from the 1990s onward and peaks between 2000 and 2015 (Fig. 6A). The most common item types carrying production dates were jerry cans (30%), drink containers (16%), and buckets (13%). Expiration dates were documented on 760 items, concentrated almost entirely on PET beverage bottles (90%) and spanning 1996–2029, with the majority falling in the 2020s (Fig. 6B). Expiration-dated items were overwhelmingly concentrated in the PNMS (31%) and MHI (65%), with almost none in the NPGP (4%), consistent with the near-absence of PET bottles in the offshore gyre. Estimated time at sea, derived by subtracting production year from collection year, revealed maximum residence times approaching 60 years (Fig. S2), with the NPGP showing a broader distribution of older material (5–40+ years) compared to the MHI and PNMS, which were skewed toward items less than 5 years old (Fig. 6C). Together, these date-based analyses reveal a dual signal: a persistent legacy stock of durable plastics circulating for decades in the gyre, overlaid with a growing influx of recently manufactured single-use packaging concentrated on island shorelines.

Polymer type, colour, and container spill signature.

HDPE (Type 2) was the most frequently identified polymer overall (2,359 of 4,925 items; 48%), dominating in the NPGP (80% of identified items there), consistent with its prevalence in durable fishing and industrial gear. PET (Type 1) was the second most abundant (2,151 items; 44%) and dominated in the PNMS (55%) and MHI (56%), reflecting the high abundance of beverage bottles in those regions (Fig. S3). Additional polymer types, PVC, LDPE, PP, and PS, occurred in comparatively low numbers. Colour distributions mirrored these compositional differences: black and white items dominated in the NPGP, consistent with fishing and aquaculture gear, whereas clear and blue items prevailed in the PNMS and MHI, reflecting the higher proportion of consumer packaging and PET beverage bottles in those regions (Fig. S4).

The ONE APUS, a container vessel that lost over 1,800 containers in the North Pacific in November 2020, provided a rare opportunity to track identifiable consumer goods as a natural tracer of debris transport across the study regions. A subset of 1,622 items across all regions was attributed to this spill. As a proportion of total cleanup mass, ONE APUS items represented 0.4–0.5% in the NPGP, 0.7–1.5% in the MHI, and 2.1–6.0% in the PNMS, with the highest value recorded at Kuaihelani in 2024 (6.0%; Fig. S5). Full polymer, colour, and ONE APUS data are provided in Supplementary Figs. S3–S6 and Supplementary Tables S1–S2.

Fishing net analysis: gear type, condition, and discard pathways

A sample of 181 net fragments greater than 50 cm, from NPGP collections in 2021 and 2023, was physically analysed and measured. Of those, 7 were determined to be cargo nets and fruit/vegetable mesh bags, while the remaining 174 were determined to be fisheries related net fragments. These nets had a combined weight of 714 kg (Fig. 7; see Supplementary Fig. S7 for photographs). All were sections of larger nets; no complete nets were recovered. Most nets were lightweight (126 of 174 weighed less than 6 kg) and small in surface area (51% measured 0–5 m^2), consistent with fragments rather than intact gear panels (Fig. 7A). Green was the dominant colour (45%), followed by grey (20%), blue (16%), and black (14%; Fig. 7B). Construction was highly uniform: among 140 nets assessed, 87% were 3-strand, 90% were knotted, and 86% had Z-twist configuration (Fig. 7C). Mesh sizes ranged from 5–550 mm but were concentrated between 40–150 mm, consistent with commercial trawl net specifications targeting demersal fish, shrimp, and other commercially important species. Based on expert assessment, nearly all nets were identified as trawl nets; static gear types such as gillnets were absent from the sample.

Despite their potential long drift histories, most nets showed limited physical wear: 72% exhibited almost no structural damage. However, the pattern of edge damage was highly diagnostic of the likely pathway of ocean entry (Fig. 7D). Of 174 nets assessed, 76 (44%) had all sides cut, and a further 36 (21%) had three sides cut and one torn, together indicating deliberate sectioning consistent with net repair and replacement practices. Only 23 nets (13%) had all sides ripped or torn, the pattern expected from accidental entanglement or gear loss (Richardson et al., 2019; Strietman, 2021). Condition assessment

based on biofouling, fraying, and fading classified 61% of nets as relatively recent, with an estimated time at sea of less than five years (Fig. 7E).

Combining edge-damage classification with expert judgement, 87% of nets were assessed as showing characteristics most consistent with inadequate fishing gear waste management rather than accidental loss (Fig. 7F). Expert consultations identified the Northwest Pacific as the most probable region of origin, with a proportion of nets plausibly linked to Chinese trawl fisheries based on material and construction characteristics, though a substantial share remained unattributed at fleet or country level due to widespread standardisation of gear design across regional fleets (Supplementary Table S3).

Discussion

The decade-long, multi-region dataset presented here provides the most comprehensive empirical account of floating plastic provenance in the North Pacific Subtropical Gyre system to date. Its findings are unambiguous on several fronts: sea-based sources dominate, fishing activity is the primary contributor by weight, and inadequate onboard waste management, rather than accidental gear loss alone, emerges as a key pathway by which fishing net fragments reach the open ocean. While land-based sources are widely considered the dominant entry point for plastics into the ocean globally, particularly for denser, more degradable materials that do not persist at the surface, what enters the ocean and what accumulates on its surface are not the same. The buoyant, durable debris concentrating across the North Pacific subtropical gyre system is disproportionately sea-based, a finding with direct consequences for how mitigation efforts should be prioritised, as developed in the sections below.

Regional patterns reveal a system shaped by oceanography and the source sector

The geographic contrast in debris composition between the NPGP, PNMS, and MHI reflects fundamentally different stages of the debris lifecycle and different dominant inputs. The NPGP functions as a long-term reservoir in which primarily durable, buoyant fishing gear, nets, lines, floats, and hard plastic gear components, dominates debris mass alongside a substantial fraction of durable hard plastic items and fragments, all retained over multi-decadal timescales through large-scale gyre circulation. The PNMS and MHI, by contrast, are dynamic interception zones that capture both the chronic output of the gyre and episodic inputs from regional maritime activity. This distinction determines how debris surveys should be designed and interpreted: offshore gyre sampling and island shoreline cleanup data are complementary, not interchangeable, and both are needed to characterise the full system.

The high abundance of floats, buoys, and PET beverage bottles in the PNMS and MHI relative to the NPGP reflects the physical behaviour of these items: spherical floats, buoys, and capped PET bottles exhibit high buoyancy and elevated windage, making them susceptible to rapid wind-driven expulsion from the gyre toward downstream island environments (Fig. 8). The NPGP is not a static feature; its position shifts seasonally and interannually, periodically bringing it closer to or farther from the Hawaiian archipelago (Lebreton et al., 2018; Maximenko et al., 2018), and during periods of proximity, high-windage items may be rapidly advected toward the PNMS and MHI before accumulating sufficient

residence time in the gyre. The near-absence of older PET bottles in the dataset further reflects the material properties of PET itself: unlike HDPE and PP, which are positively buoyant and can remain afloat for decades, PET is negatively buoyant and prone to sinking once it loses structural integrity or becomes fouled (Andrady, 2011; Reisser et al., 2014). With material weight loss rates in marine environments estimated at 3–5% per year, considerably higher than the < 1% per year recorded for PE (Gerritse et al., 2020), PET bottles degrade and fragment on comparatively short timescales. Uncapped bottles, which represented approximately 18% of PET bottles in our dataset (n = 2,103; ranging from 8.4% in the PNMS and 10.0% in the MHI to 36.4% in the NPGP), are particularly susceptible to waterlogging and rapid loss of buoyancy, further reducing their residence time at the surface. The markedly higher proportion of uncapped bottles in the NPGP (36.4%) compared to island sites (8.4–10.0%) is consistent with this mechanism: bottles that retain their caps remain buoyant longer and are more susceptible to wind-driven transport toward downstream environments, while uncapped bottles lose buoyancy more rapidly and are more likely to remain in the gyre and sink before reaching or escaping the gyre. Together, these material properties mean that older PET bottles are unlikely to survive long enough to accumulate in the gyre in the same way as more durable polyolefins, and that the PET bottles we do observe represent a predominantly recent and transient signal rather than a legacy one.

This mechanism explains why the NPGP is relatively depleted in items that are abundant on Hawaiian shorelines, and why the PNMS and MHI, positioned downstream of the NPGP and closer to major maritime traffic routes, receive a disproportionate share of recently released floating debris. Vessel-derived waste from maritime traffic transiting near Hawaiian waters may contribute as a secondary source, particularly for PET bottles, and is discussed further in Supplementary Discussion SD2. The ONE APUS container spill of November 2020 further illustrates how proximity to a spill location, rather than transport through the gyre, can determine debris distribution across regions. The spill occurred at approximately 33°04'N, 172°52'E, approximately 1,600 nautical miles northwest of Hawaii, geographically much closer to the PNMS and MHI than to the NPGP accumulation zone (JTSB, 2024). Of 1,622 identified spill-derived items recovered across all three regions, the proportional contribution to total cleanup mass was markedly higher in the PNMS (2.1–6.0%) and MHI (0.7–1.5%) than in the NPGP (0.4–0.5%), with the highest value recorded at Kuaihelani, the most exposed and closest island to the spill, in 2024 (6.0%; Fig. 8). The higher proportional recovery at island sites therefore reflects proximity to the spill location and wind-driven transport toward the Hawaiian archipelago rather than gyre-mediated transport, providing a rare and well-constrained natural tracer of debris dispersal dynamics across the North Pacific. Full details of spill item composition, brand distribution, and temporal patterns are provided in Supplementary Discussion SD3.

Beyond episodic inputs, the elevated item counts in the MHI, despite its comparatively low total mass, reflect intensified fragmentation in high-energy nearshore environments where wave action, UV exposure, and repeated beaching and resuspension cycles break down larger debris into numerous smaller pieces (Andrady et al., 2022; Morales-Caselles et al., 2021). This process amplifies item counts without a proportional increase in mass, underscoring that abundance and mass metrics capture fundamentally different aspects of debris impacts and must be interpreted jointly. The composition of

debris recovered from island shorelines is shaped not only by transport dynamics but also by the history of human intervention at each site. Frequent shoreline cleanups at the PNMS (yearly) and MHI (monthly) preferentially remove stranded material, meaning that debris assemblages at these sites reflect predominantly recent inputs rather than the long-term accumulation of both newer and legacy debris that characterises the NPGP, which has never been systematically cleaned prior to The Ocean Cleanup operations. This difference in accumulation history provides an important additional explanation for the observed regional contrasts in debris age and composition: comparisons between gyre and island environments partly reflect differences in sampling context rather than source differences alone. Collection methodology introduces additional size-selective biases: the cleanup systems used in the NPGP are designed to retain material above approximately 1.5 cm, potentially underrepresenting the smallest fragments that are more readily collected during manual shoreline cleanups, while large-scale island cleanups may prioritise recovery by weight, introducing a bias toward larger objects. These methodological differences are unlikely to alter the principal findings of this study, which are based on items greater than 5 cm with identifiable provenance markers, but they should be considered when interpreting regional differences in item counts and size distributions.

East Asian dominance and a striking regional asymmetry in fishing gear provenance

The North Pacific Subtropical Gyre acts as a major convergence zone for buoyant debris originating from the surrounding rim countries, with the Kuroshio Current and North Pacific Current serving as the primary conveyor systems transporting material from East Asian coasts and fishing grounds eastward into the gyre accumulation zone (Lebreton et al., 2019). Modelling studies have shown that debris released in the western and central North Pacific follows multi-year to multi-decadal transport pathways before reaching the NPGP, with residence times strongly dependent on initial release location, particle buoyancy, and windage (Lebreton et al., 2019, 2022). This physical framework provides the essential context for interpreting the provenance patterns observed in this dataset.

The provenance analysis of 19,768 individually examined items confirms that the majority of identifiable debris bears markings associated with East Asian countries, particularly China and Japan, with South Korea, Indonesia, and the United States contributing smaller but consistent fractions across all three regions and both debris categories. This is consistent with earlier work by Lebreton et al. (2019, 2022), who identified industrialised fishing nations of the Northwest Pacific as the largest contributors to floating plastic mass in the NPGP based on a dataset of 655 kg of debris; the present study extends these findings substantially, with over 55,893 kg of debris collected across the NPGP, PNMS, and MHI, providing item-level provenance resolution across three complementary environments, including downstream island sites not previously covered, that together allow the full dynamics of debris transport, accumulation, and stranding to be examined at this scale for the first time. This finding is robust across multiple independent lines of evidence, written language, production country, brand identity, and polymer type, and confirms that international cooperation among North Pacific nations, particularly within East Asia, is essential for effective source reduction. While these patterns point consistently toward East Asian origin, markings reflect manufacturing location, language region, or market distribution rather than

the nationality of the vessel or fleet responsible for the item's loss; in a globalised fishing sector, gear produced in one country is routinely deployed by fleets operating under another flag state, and provenance markers should therefore be treated as probabilistic indicators of source rather than definitive attribution.

The most striking finding in the provenance dataset is a regional asymmetry between gear bearing Japanese markings dominating ALDFG in the NPGP and gear bearing Chinese markings dominating ALDFG in the PNMS and MHI. This pattern is reproducible across item types, floats, buoys, crates, and baits, all of which show the same divergence, though the asymmetry may partly reflect differences in debris age, transport history, and accumulation dynamics rather than distinct contemporary source dominance patterns alone. Two non-mutually exclusive explanations may account for this pattern. First, temporal legacy accumulation: Japanese-labelled gear has had decades to accumulate within the subtropical gyre through the convergent Kuroshio-driven circulation described by Lebreton et al. (2019), building up a legacy signal that reflects the historical dominance of Japanese fishing effort in this region rather than contemporary inputs alone. Critically, this asymmetry cannot be explained by differences in windage or physical transport behaviour between Japanese and Chinese gear, since both consist of similar item types with comparable buoyancy and drift characteristics – the asymmetry is therefore primarily temporal rather than physical. This interpretation is consistent with the well-documented contraction of Japanese distant-water activity in the North Pacific, where longline fishing effort declined continuously from approximately 200 million hooks in the 1980s to 100 million hooks by the early 2000s and has continued to fall since (Fisheries Agency of Japan, 2024). Second, a recent shift in fleet composition: up to the mid-1990s, the global distant-water fleet was dominated by Japan, but Chinese and Taiwanese fleets subsequently expanded dramatically to become the leading distant-water fishing nations, with the Northwest Pacific among their most frequent areas of operation (Kroodsma et al., 2018). Chinese-labelled ALDFG on Hawaiian shorelines therefore most plausibly represents gear that has entered the system more recently and has not yet had sufficient time to accumulate within the gyre to the same degree as the older Japanese legacy material. Importantly, the presence of Chinese-labelled items at island sites may also reflect that the PNMS and MHI function as downstream interception and accumulation zones receiving material advected from the broader North Pacific, rather than necessarily representing debris expelled directly from the NPGP itself. In other words, the asymmetry reflects when gear entered the ocean and how long it has been circulating, not how it behaves physically once afloat: newer Chinese-labelled gear is reaching Hawaiian shorelines before sufficient time has elapsed for it to build up in the gyre, while older Japanese-labelled gear has been accumulating in the NPGP for decades.

The 2011 Tohoku earthquake and tsunami introduced an exceptionally large pulse of Japanese-origin debris into the North Pacific, including fishing gear, vessels, and consumer products, some of which reached Hawaiian beaches and contributed to the accumulation of Japanese-labelled material in the gyre (Maximenko et al., 2018). While our dataset cannot distinguish tsunami-derived items from fishing-related inputs, this event likely contributes to the elevated representation of Japanese-origin debris in the NPGP and should be considered alongside the fleet legacy hypothesis. As discussed above, the periodic cleanup regime at island sites means that their assemblages predominantly reflect recent inputs, further

reinforcing the interpretation that Chinese-labelled ALDFG on Hawaiian shorelines represents newer gear entering the system now, while the gyre retains the older Japanese legacy. Notably, a small number of items dating to the 1960s were recovered on Molokai and O'ahu in the MHI, demonstrating that even very old material can eventually strand on Hawaiian beaches after decades of oceanic circulation, likely reflecting episodic transport of legacy plastics from the gyre during periods of closer proximity to the archipelago. If correct, this interpretation carries a forward-looking implication: as Japanese fleet activity continues to decline and Chinese, and increasingly Indonesian and other Asian fleet, activity grows, Chinese-labelled ALDFG should progressively dominate the gyre signal in the coming decades, just as it already dominates on the islands today. The regional debris signature we observe may therefore be not only a temporal archive of past fleet transitions, but also a leading indicator of the debris composition we should expect in the NPGP in the future. Resolving these mechanisms, through integration of production date data, oceanographic dispersal modelling, and historical fishing effort records, represents one of the most compelling and tractable questions this dataset opens for future work.

Brand analysis is consistent with this picture: Chinese float and buoy manufacturers and beverage brands dominate identifiable branded items overall, while Japanese float manufacturers are disproportionately represented in the NPGP, a dual signal that mirrors the transport model proposed by Lebreton et al. (2022) and, for the first time, can be verified empirically across complementary offshore and shoreline environments.

Production and expiration date analyses add a powerful temporal dimension to the provenance picture. Production dates spanning more than six decades confirm that the NPGP harbours a genuine multi-decadal legacy of durable plastics, with some items potentially having circulated for up to 60 years. This record, however, represents a highly filtered subset of debris, specifically those materials sufficiently buoyant, durable, and resistant to fragmentation to persist within the gyre, and selective transport, degradation, windage, and sampling mesh size all shape which items are ultimately recovered. The production date distribution captures a brief but notable dip between 2020 and 2022 followed by a sharp rebound in 2023, a pattern consistent with reduced industrial and maritime activity during the COVID-19 pandemic, though variability in cleanup effort and timing across sites may also contribute (Supplementary Discussion SD1). Expiration-dated items, concentrated almost entirely on recent PET beverage bottles in the PNMS and MHI, are consistent with a growing influx of newly manufactured single-use packaging reaching island shorelines, though their concentration at island sites may also partly reflect the shorter effective accumulation window resulting from periodic cleanups, which preferentially remove older stranded debris. Together, these temporal patterns confirm that the NPGP functions as a slowly evolving archive of past industrial and maritime activity, while the island environments capture a continuously refreshed record of present inputs, a distinction that future monitoring programmes should explicitly account for in study design and interpretation.

Onboard waste management as a primary pathway for fishing net inputs

The fishing net analysis delivers one of the most policy-relevant findings of this study: 87% of trawl net fragments recovered from the NPGP showed characteristics most consistent with inadequate fishing gear waste management practices rather than accidental gear loss. This conclusion rests on multiple converging lines of evidence, the predominance of clean, regular cut edges, minimal physical wear, short estimated residence times, and small fragment sizes consistent with repair offcuts rather than intact accidentally lost gear, and is robust across three independent collection events spanning 2021 and 2023. The evidence suggests that a substantial proportion of net material reaching the NPGP originates not from the unavoidable consequences of storms or operational accidents, but from discarded net fragments generated during routine repair and replacement that are not adequately collected and stored, whether at sea during fishing operations or upon return to port, before ultimately entering the ocean.

This finding has direct implications for mitigation. If inadequate gear waste management across the full lifecycle of net use, from vessel to port, is indeed a primary pathway, then interventions targeting both onboard infrastructure and port reception facilities, including mandatory waste retention requirements at sea, improved port collection systems, and strengthened enforcement of existing MARPOL Annex V provisions, are likely to be among the most effective tools available to reduce fishing net inputs to the North Pacific. The fact that most recovered nets are estimated to be less than five years old further suggests that contemporary inputs continue to contribute substantially to debris accumulation alongside older legacy material, making timely intervention all the more important.

The consistent construction characteristics of recovered nets, 3-strand, knotted, Z-twist, 40–150 mm mesh, point to large-scale commercial trawl gear, with the Northwest Pacific identified as the most probable region of origin through expert consultation. While precise fleet attribution remains challenging due to the standardisation of gear design across regional fleets, the hard plastic ALDFG provenance data independently confirms East Asian source dominance in the offshore debris pool; this signal cannot, however, be attributed to trawl fisheries specifically, as floats, buoys, crates, and other hard plastic items are used across a wide range of fishery types. Future work combining material fingerprinting, dye signature analysis, and dispersal modelling integrated with global fishing effort datasets offers a clear path toward more resolved source attribution, and the methodological framework developed here provides a replicable foundation for such efforts. The apparent paradox of abundant trawl net fragments accumulating in a remote offshore gyre far from any active trawling grounds, and the potential role of mesoscale eddies as hotspots of ALDFG generation, are discussed further in Supplementary Discussion SD4.

Taken together, the findings presented in this study make a compelling case that persistent offshore floating debris accumulating across the North Pacific subtropical gyre system is fundamentally shaped by sea-based sources, driven by fishing activity, and sustained by inadequate gear waste management practices that allow net fragments and other fishing-related materials to enter the ocean at scale, whether through direct disposal at sea or through insufficient port waste infrastructure. These findings pertain to a specific and selective fraction of marine litter, the buoyant, durable debris that survives multi-year oceanic transport to accumulate in offshore convergence zones, and should not be generalised to

coastal, submerged, or seabed environments, where the balance of sources and the composition of debris may look fundamentally different. The geographic signal is clear, the temporal signal is consistent, and the gear condition analysis points toward preventable rather than inevitable pathways of ocean entry. Tackling marine plastic pollution in its entirety will ultimately require a compartment-specific approach that recognises the distinct source structures, transport dynamics, and mitigation levers relevant to each debris fraction. For the persistent offshore floating fraction studied here, the path forward requires international cooperation, cross-sectoral engagement, and a recognition that consumer demand, for fish and for the products that accompany modern life, drives both the fishing activity dominating the gyre and the consumer packaging accumulating on downstream island shorelines.

Methods

Study sites and sample collection

Plastic marine debris was collected across three regions of the North Pacific: the NPGP, the PNMS, and the MHI. The NPGP represents the most offshore site, situated within the subtropical gyre circulation, where floating debris accumulates through large-scale oceanographic convergence. The PNMS, comprising Kamole/Kauō (Laysan), Kuaihelani, and Kapou Islands, is located in the Northwestern Hawaiian Islands downstream of the NPGP. The MHI, represented by Kalaupapa (Moloka□i) and Kahuku (O□ahu), lies farther south and is more strongly influenced by regional oceanographic processes.

The Ocean Cleanup collected debris from the NPGP during cleanup operations in 2015, 2019, 2021, 2023, and 2024, using surface trawl nets (2015) and cleanup systems (Systems 001/B, 002, and 03) across seven datasets, yielding a combined 24,202 kg, representing a fraction of the total mass collected during these operations. The Papahānaumokuākea Marine Debris Project (PMDP) oversaw collections at Kamole, Kuaihelani, and Kapou Islands between 2024 and 2025, totaling 22,190 kg. Sustainable Coastlines Hawai□i (SCH) coordinated collections across O□ahu and Moloka□i through 45 small-scale monthly cleanups at Kahuku Beach and three large-scale cleanups at Kahuku and Kalaupapa between 2024 and 2025, with a combined mass of 8,745 kg. All collected material consisted of items larger than approximately 1.6 cm in maximum dimension. Full collection dates, coordinates, weights, and cleanup effort are provided in Supplementary Table S1.

Debris classification and provenance analysis

Following each cleanup, debris was transported to sorting facilities and systematically divided into two fractions: nets and ropes (fibers) and hard plastics (rigids; Supplementary Fig. S8). Fibers were dried, weighed, and stored. Hard plastic items and fragments greater than 5 cm were sorted individually into 112 predefined categories across nine material types following the OSPAR Beach Litter Monitoring Guidelines (OSPAR, 2010), with additional subcategories added for items frequently observed in the study area, including eel traps, baits, and oyster spacers (Lebreton et al., 2022). Each item was assigned a category, counted, and weighed. Representative examples of the most commonly recovered item types

bearing identifiable origin markers, including buoys and floats, crates, aquaculture gear, cleaner and beverage bottles, and caps and lids, are illustrated in Supplementary Fig. S9.

A total of 19,768 hard plastic items bearing identifiable source markers were individually examined for evidence of production country, written language, brand, polymer type, and production or expiration dates. Country association was attributed from language markings only where the language was spoken in a single country; English and Spanish were excluded as standalone origin indicators. Brand origin was determined by identifying the country of company's establishment via publicly available sources. Polymer type was identified using recycling codes and, for a subset of items, attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) following established protocols (Jung et al., 2018). Items from the ONE APUS container spill were identified based on item type and brand. Full classification criteria, category lists, and identification protocols are provided in Supplementary Methods S2.

Fishing net analysis

A total of 181 net fragments greater than 50 cm were collected from the NPGP across three extraction events in 2021 and 2023 and analysed at a controlled warehouse facility in the Netherlands. Each net was untangled, spread out, and assessed following the Fishing Net Assessment Protocol (Strietman, 2021), which provides a systematic framework for characterizing recovered nets from sea surface collections. As part of this assessment, fragments were also classified according to their likely functional origin (e.g. fisheries-related nets, cargo nets, or fruit/vegetable mesh bags). Of the 181 analysed fragments, seven were identified as cargo nets or fruit/vegetable mesh bags, while the remaining 174 were classified as fisheries-related net fragments. Physical and morphological characteristics recorded included weight, overall dimensions, surface area, mesh size, number of pieces, construction type, twist direction, twine diameter, and number of strands. Polymer composition was determined using ATR-FTIR (Agilent Cary 630 FTIR). Indicators of environmental exposure, biofouling, fraying, and fading were recorded to estimate relative time at sea, classifying nets as relatively recent (less than 5 years) or older.

The configuration of cut versus torn edges on each side of the 174 fisheries-related net fragments was assessed to infer the most probable pathway by which each net entered the marine environment, distinguishing accidental loss from intentional discard during repair or maintenance operations. Expert input on gear type, fishery sector, and geographic origin was collected from 18 specialists across the North Pacific region through structured consultations (Supplementary Table S3). Full protocol details and expert consultation methodology are provided in Supplementary Methods S3.

Declarations

Acknowledgements

The authors express their deepest gratitude to the staff and volunteers of Sustainable Coastlines Hawai□i and the Papahānaumokuākea Marine Debris Project for their extraordinary dedication and countless hours of fieldwork that made this dataset possible. Their tireless commitment to collecting plastic debris from some of the most remote and ecologically precious environments on Earth represents both a scientific and environmental contribution of the highest order. The authors also sincerely thank the captains and crews of The Ocean Cleanup vessels for their professionalism and dedication during expeditions to the North Pacific Garbage Patch, without whom the offshore collections would not have been possible. The authors acknowledge with respect the Native Hawaiian communities and cultural stewards of Papahānaumokuākea, whose deep connection to these islands and surrounding waters provides an enduring reminder of the importance of protecting this extraordinary environment. The authors also sincerely thank the 18 fishing gear experts who generously contributed their time and expertise to help characterise recovered fishing nets and interpret their provenance and discard pathways, and the translators who assisted with the identification of foreign-language markings on recovered debris items during catch analysis. Finally, the authors are grateful to The Ocean Cleanup donors whose generous support sponsored this research.

Author contributions

S.-J.R. and L.L. conceived and designed the study. S.-J.R. led the data collection and analysis across all three regions, oversaw the sorting and classification of debris at the NPGP, MHI, and PNMS sites, including Kapou and Kamole Islands, performed the provenance analysis of hard plastic items, coordinated all aspects of the study, and led the writing of the manuscript. M.E. developed and implemented the initial catch analysis methodology and contributed to data interpretation, manuscript review, and editing. W.-J.S. implemented the Fishing Net Assessment Protocol, led the physical and morphological assessment of recovered fishing nets, and helped perform fishing net data processing, coordinated expert consultations on gear type and origin, and contributed to the writing of the fishing net sections. P.P. assisted with the fishing net assessment and contributed to manuscript review and editing. R.B. led and coordinated debris collections for Sustainable Coastlines Hawai□i across the Main Hawaiian Islands and contributed to manuscript review and editing. K.O. led and coordinated debris collections for the Papahānaumokuākea Marine Debris Project across the Northwestern Hawaiian Islands, oversaw the sorting and classification of debris at PNMS sites (Kuaihelani), and contributed to manuscript review and editing. L.L. contributed to study conception, oceanographic interpretation, data analysis, and manuscript review and editing. All authors read and approved the final version of the manuscript.

Data availability

The datasets generated and analysed during this study will be made publicly available upon acceptance in a recognised open data repository. Data supporting the findings are provided in the Supplementary Information and Supplementary Data Files 1 and 2. Additional data are available from the corresponding author upon reasonable request.

References

1. (UNEP), U.N.E.P., 2022. From pollution to solution: A Global Assessment of Marine Litter and Plastic Pollution.
2. Andrady, A.L., 2011. Microplastics in the marine environment. Mar. Pollut. Bull. 62, 1596–1605. https://doi.org/10.1016/j.marpolbul.2011.05.030
3. Andrady, A.L., Barnes, P.W., Bornman, J.F., Gouin, T., Madronich, S., White, C.C., Zepp, R.G., Jansen, M.A.K., 2022. Oxidation and fragmentation of plastics in a changing environment; from UV-radiation to biological degradation. Sci. Total Environ. 851, 158022. https://doi.org/10.1016/j.scitotenv.2022.158022
4. Apete, L., Martin, O. V., Iacovidou, E., 2024. Fishing plastic waste: Knowns and known unknowns. Mar. Pollut. Bull. 205, 116530. https://doi.org/10.1016/j.marpolbul.2024.116530
5. Chamas, A., Moon, H., Zheng, J., Qiu, Y., Tabassum, T., Jang, J.H., Abu-Omar, M.M., Scott, S.L., Suh, S., 2020. Degradation Rates of Plastics in the Environment. ACS Sustain. Chem. Eng. 8, 3494–3511. https://doi.org/10.1021/acssuschemeng.9b06635
6. Dijkstra, H., 2025. The Henderson Island microcosm : plastic pollution accumulation in the. Mar. Pollut. Bull. 219, 118095. https://doi.org/10.1016/j.marpolbul.2025.118095
7. Fisheries Agency of Japan, 2024. National Report of Japan. Document ISC/24/PLENARY-06. International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC), 24th Plenary Meeting.
8. Gerritse, J., Leslie, H.A., Tender, C.A. De, Devriese, L.I., Vethaak, A.D., 2020. Fragmentation of plastic objects in a laboratory seawater microcosm. Sci. Rep. 1–16. https://doi.org/10.1038/s41598-020-67927-1
9. GESAMP, 1990. The State of the Marine Environment. Geneva.
10. Hudson, A., Gilardi, K., Vousden, D., 2025. The 80 : 20 estimate of land vs . ocean sources of marine pollution : fi t for purpose ? 1–3. https://doi.org/10.3389/fmars.2025.1587805
11. Jung, M.R., Horgen, F.D., Orski, S. V., Rodriguez C., V., Beers, K.L., Balazs, G.H., Jones, T.T., Work, T.M., Brignac, K.C., Royer, S.-J.J., Hyrenbach, K.D., Jensen, B.A., Lynch, J.M., 2018. Validation of ATR FT-IR to identify polymers of plastic marine debris, including those ingested by marine organisms. Mar. Pollut. Bull. 127, 704–716. https://doi.org/10.1016/j.marpolbul.2017.12.061
12. Kaandorp, M.L.A., Lobelle, D., Kehl, C., Dijkstra, H.A., Van Sebille, E., 2023. Global mass of buoyant marine plastics dominated by large long-lived debris. Nat. Geosci. 16. https://doi.org/10.1038/s41561-023-01216-0
13. Kroodsma, D.A., Mayorga, J., Hochberg, T., Miller, N.A., Boerder, K., Ferretti, F., Wilson, A., Bergman, B., White, T.D., Block, B.A., Woods, P., Sullivan, B., Costello, C., Worm, B., 2018. Tracking the global footprint of fisheries. Science 908, 904–908.
14. Kühn, S., Rebolledo Bravo, E.L., van Franeker, J.A., 2015. Deleterious Effects of Litter in Marine Life, in: Marine Anthopogenic Litter. pp. 75–116.

15. Lavers, J.L., Bond, A.L., 2017. Exceptional and rapid accumulation of anthropogenic debris on one of the world's most remote and pristine islands. Proc. Natl. Acad. Sci. U. S. A. 114, 201619818. https://doi.org/10.1073/pnas.1619818114
16. Lebreton, L., Egger, M., Slat, B., 2019. A global mass budget for positively buoyant macroplastic debris in the ocean. Sci. Rep. 10, 58755. https://doi.org/10.1038/s41598-019-49413-5
17. Lebreton, L., Royer, S.-J., Peytavin, A., Strietman, W.J., Smeding-Zuurendonk, I., Egger, M., 2022. Industrialised fishing nations largely contribute to floating plastic pollution in the North Pacific subtropical gyre. Sci. Rep. 12, 1–11. https://doi.org/10.1038/s41598-022-16529-0
18. Lebreton, L., Slat, B., Ferrari, F., Sainte-Rose, B., Aitken, J., Marthouse, R., Hajbane, S., Cunsolo, S., Schwarz, A., Levivier, A., Noble, K., Debeljak, P., Maral, H., Schoeneich-Argent, R., Brambini, R., Reisser, J., 2018. Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. Sci. Rep. 8, 1–18. https://doi.org/10.1038/s41598-018-22939-w
19. Lebreton, L.C.M., van der Zwet, J., Damsteeg, J.-W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8, 15611. https://doi.org/10.1038/ncomms15611
20. Maximenko, N., Hafner, J., Kamachi, M., Macfadyen, A., 2018. Numerical simulations of debris drift from the Great Japan Tsunami of 2011 and their verification with observational reports. Mar. Pollut. Bull. 132, 5–25. https://doi.org/10.1016/j.marpolbul.2018.03.056
21. Meijer, L.J.J., Emmerik, T. Van, Ent, R. Van Der, Schmidt, C., Lebreton, L., 2021. More than 1000 rivers account for 80 % of global riverine plastic emissions into the ocean. Sci. Adv. 1–14.
22. Molina-padrón, N., Cabrera-almeida, F., Araña-pulido, V., 2024. Towards a Global Surveillance System for Lost Containers at Sea. J. Mar. Sci. Eng. 12, 1–20.
23. Morales-Caselles, C., Viejo, J., Martí, E., González-Fernández, D., Pragnell-Raasch, H., González-Gordillo, J.I., Montero, E., Arroyo, G.M., Hanke, G., Salvo, V.S., Basurko, O.C., Mallos, N., Lebreton, L., Echevarría, F., van Emmerik, T., Duarte, C.M., Gálvez, J.A., van Sebille, E., Galgani, F., García, C.M., Ross, P.S., Bartual, A., Ioakeimidis, C., Markalain, G., Isobe, A., Cózar, A., 2021. An inshore–offshore sorting system revealed from global classification of ocean litter. Nat. Sustain. 4, 484–493. https://doi.org/10.1038/s41893-021-00720-8
24. NOAA Marine Debris Program, 2021. 2021 Hawai'i Marine Debris Action Plan.
25. OSPAR, 2010. Guideline for monitoring marine litter on the beachs in the OSPAR Maritime Area. OSPAR Comm. 1, 84.
26. Reisser, J., Slat, B., Noble, K., du Plessis, K., Epp, M., Proietti, M., de Sonneville, J., Becker, T., Pattiaratchi, C., 2014. The vertical distribution of buoyant plastics at sea. Biogeosciences Discuss. 11, 16207–16226. https://doi.org/10.5194/bgd-11-16207-2014
27. Richardson, K., Hardesty, B.D., Wilcox, C., 2019. Estimates of fishing gear loss rates at a global scale : A literature review and meta - analysis. Fish Fish. 1–14. https://doi.org/10.1111/faf.12407
28. Richardson, K., Wilcox, C., Vince, J., Hardesty, B.D., 2021. Challenges and misperceptions around global fishing gear loss estimates. Mar. Policy 129, 104522.

https://doi.org/10.1016/j.marpol.2021.104522

29. Royer, S.-J., Corniuk, R., McWhirter, A., Lynch, H.W., Pollock, K., O'Brien, K., Escalle, L., Stevens, K., Moreno, G., Lynch, J.M., 2023. Large floating derelict fishing gear is frequent marine pollution in the Hawaiian Islands and Palmyra Atoll. Mar. Pollut. Bull. 196, 115585. https://doi.org/10.1016/j.marpolbul.2023.115585
30. Saliba, M., Frantzi, S., Beukering, P. Van, 2022. Shipping spills and plastic pollution : A review of maritime governance in the North Sea. Mar. Pollut. Bull. 181, 113939. https://doi.org/10.1016/j.marpolbul.2022.113939
31. Strietman, W.J., 2021. Fishing nets on the coastline of the Arctic and North-East Atlantic : a source analysis.
32. Turner, A., Williams, T., Pitchford, T., 2021. Transport , weathering and pollution of plastic from container losses at sea : Observations from a spillage of inkjet cartridges in the North Atlantic Ocean *. Environ. Pollut. 284, 117131. https://doi.org/10.1016/j.envpol.2021.117131
33. van Emmerik, T., Kieu-Le, T.-C., Loozen, M., van Oeveren, K., Strady, E., Bui, X.-T., Egger, M., Gasperi, J., Lebreton, L., Nguyen, P.-D., Schwarz, A., Slat, B., Tassin, B., 2018. A Methodology to Characterize Riverine Macroplastic Emission Into the Ocean. Front. Mar. Sci. 5, 1–11. https://doi.org/10.3389/fmars.2018.00372
34. Weinstein, J.E., Crocker, B.K., Gray, A.D., 2016. From macroplastic to microplastic: Degradation of high-density polyethylene, polypropylene, and polystyrene in a salt marsh habitat. Environ. Toxicol. Chem. 35. https://doi.org/10.1002/etc.3432

Table

Table 1 is available in the Supplementary Files section.

Figures

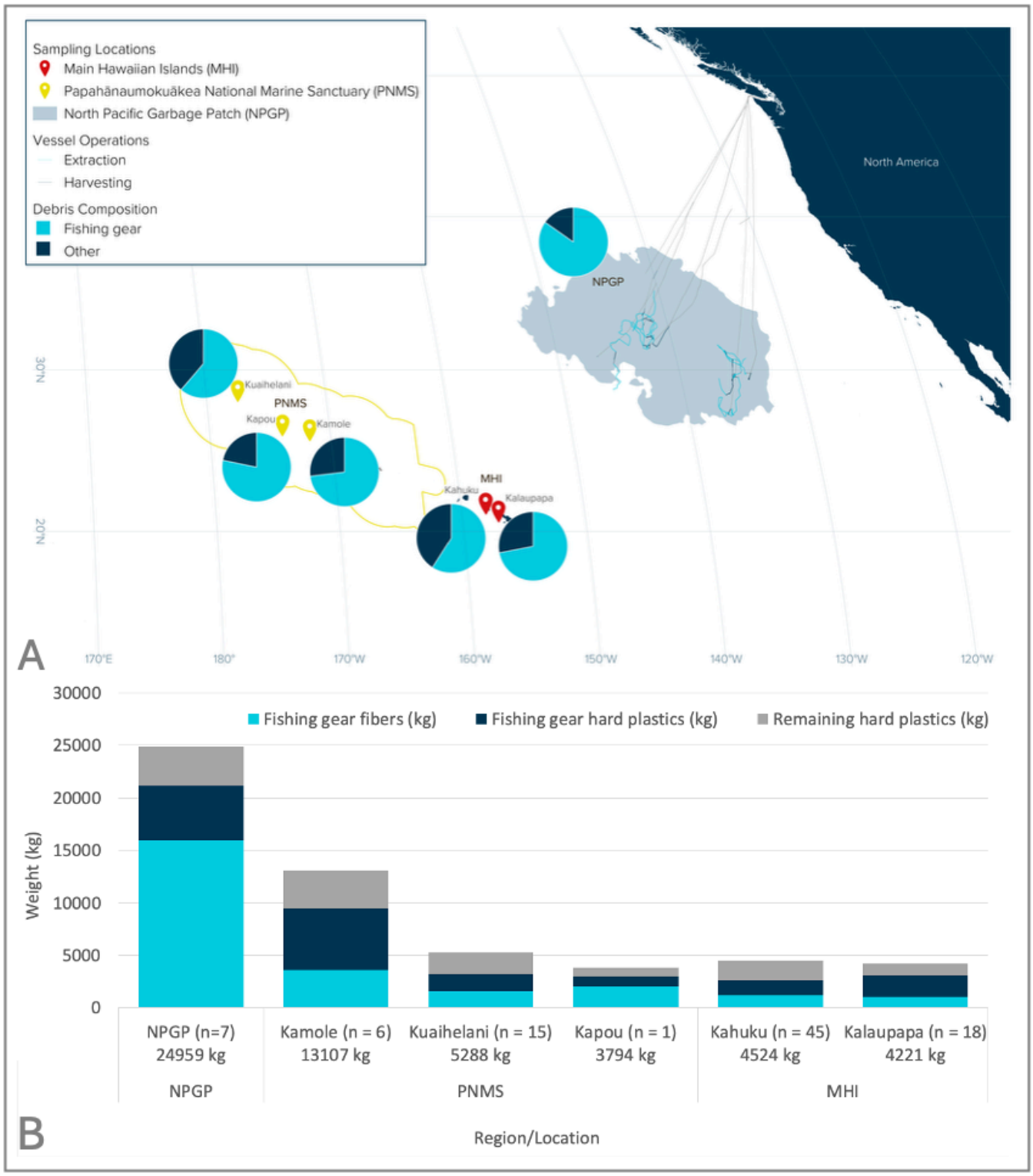


Figure 1

Maps of the three study regions, the North Pacific Garbage Patch (NPGP), the Main Hawaiian Islands (MHI), and the Papahānaumokuākea National Marine Sanctuary (PNMS). For the MHI, the location includes O□ahu and Moloka□i, while the PNMS location includes Kuaihelani/Pihemanu (Midway Atoll), Kamole/Kauō (Laysan), and Kapou/Papa□āpoho (Lisianski) Islands (A) Each location includes a pie chart showing the proportion of fishing-related debris (fishing gear fibers and hard plastics; light blue)

versus all other debris categories (navy blue). (B) Descriptive metrics of debris collected across the three study regions and the five locations. For each location, coloured bars indicate the contributions in mass (kg) of fishing-gear fibers (light blue), fishing-gear hard plastics (navy blue), and non-fishing-related hard plastics (grey) for debris >5 cm. For each location, *n* represents the number of cleanup events, and the total weight of debris collected (kg) is shown beneath the bars.

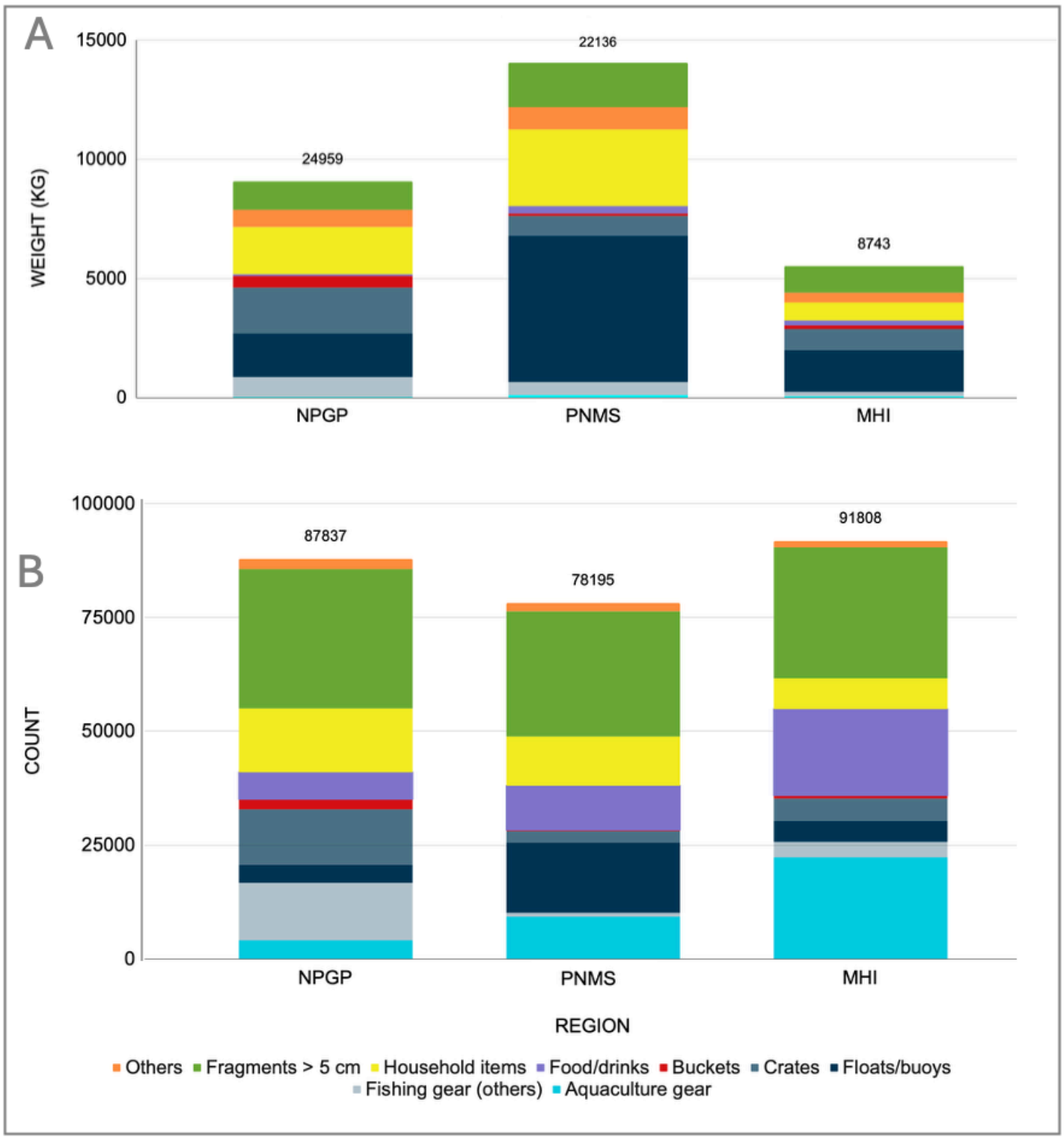


Figure 2

Debris composition by (A) total mass (kg) and (B) total item count across the North Pacific Garbage Patch (NPGP), Papahānaumokuākea National Marine Sanctuary (PNMS), and the Main Hawaiian Islands (MHI). The four lowermost segments of each bar, aquaculture gear (teal) and floats and buoys, crates, and other fishing gear items (navy and dark blue tones), collectively represent abandoned, lost, or discarded fishing gear (ALDFG) hard plastic components. The remaining upper segments, fragments greater than 5 cm, household items, food and drink items, and other items, represent hard plastics not classified as ALDFG. Numbers above each bar indicate total mass (kg) in panel A and total item count in panel B per region.

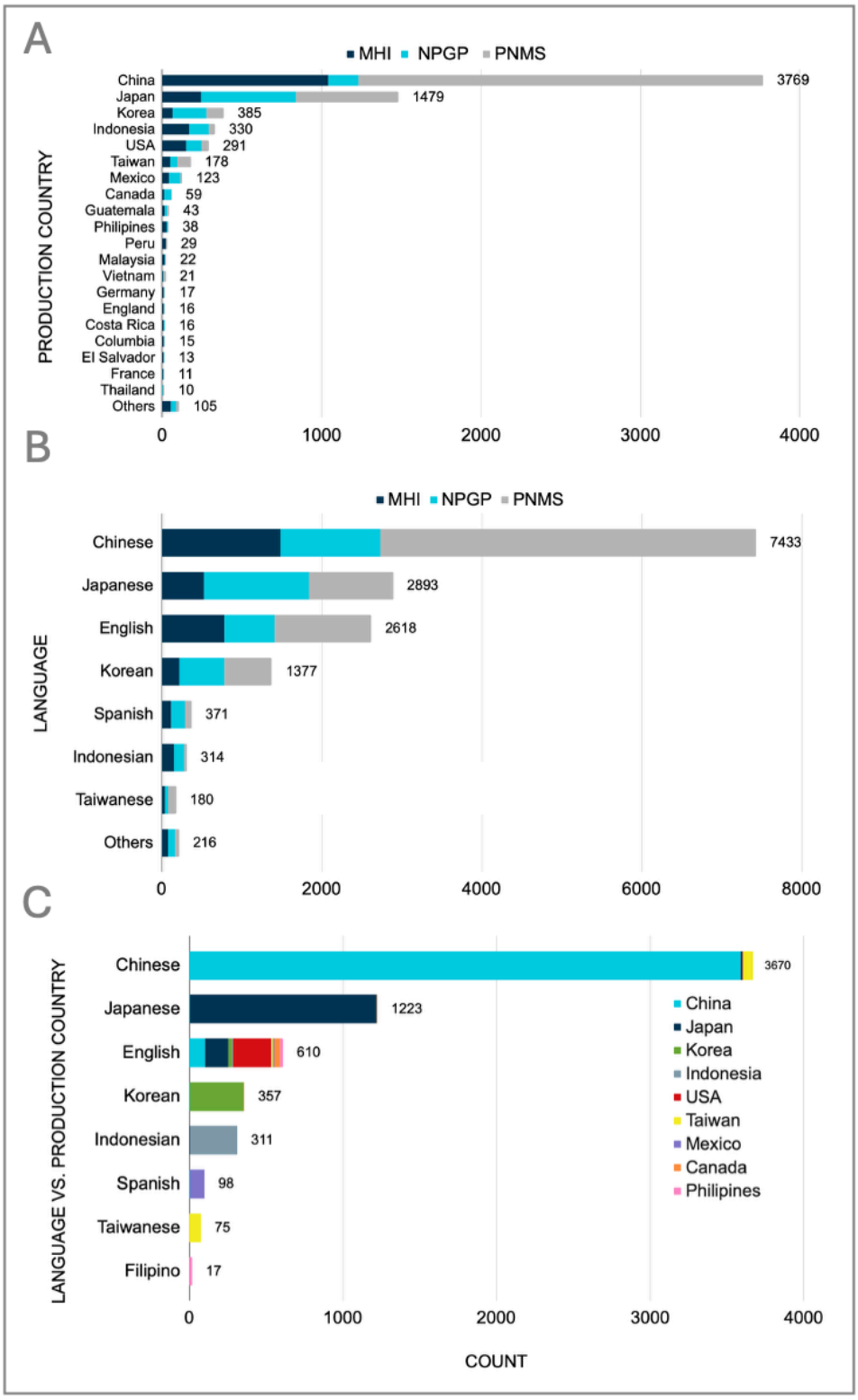


Figure 3

Production country (A), language of writing observed (B), and a cross-comparison of languages versus production countries (C) on debris collected from the Papahānaumokuākea National Marine Sanctuary (PNMS), the Main Hawaiian Islands (MHI), and the North Pacific Garbage Patch (NPGP). A. The stacked bars are divided per region and show the top 20 most frequently observed production countries on debris items, based on a total of 19,768 items with identifiable written text. Production countries

represented by fewer than ten items are labeled as others (105 items). B. The stacked bars are divided per region and show the top seven most frequently observed languages on debris items. The figure displays the relative proportions of debris labeled in Chinese, Japanese, English, Korean, Indonesian, Spanish, and Taiwanese. Languages represented by fewer items are labeled as others (216 items). C. Cross-comparison between the languages and the production countries for the three regions for the top eight and nine languages and production countries, respectively. The remaining part of the dataset is provided in the Supplementary Information (SI).

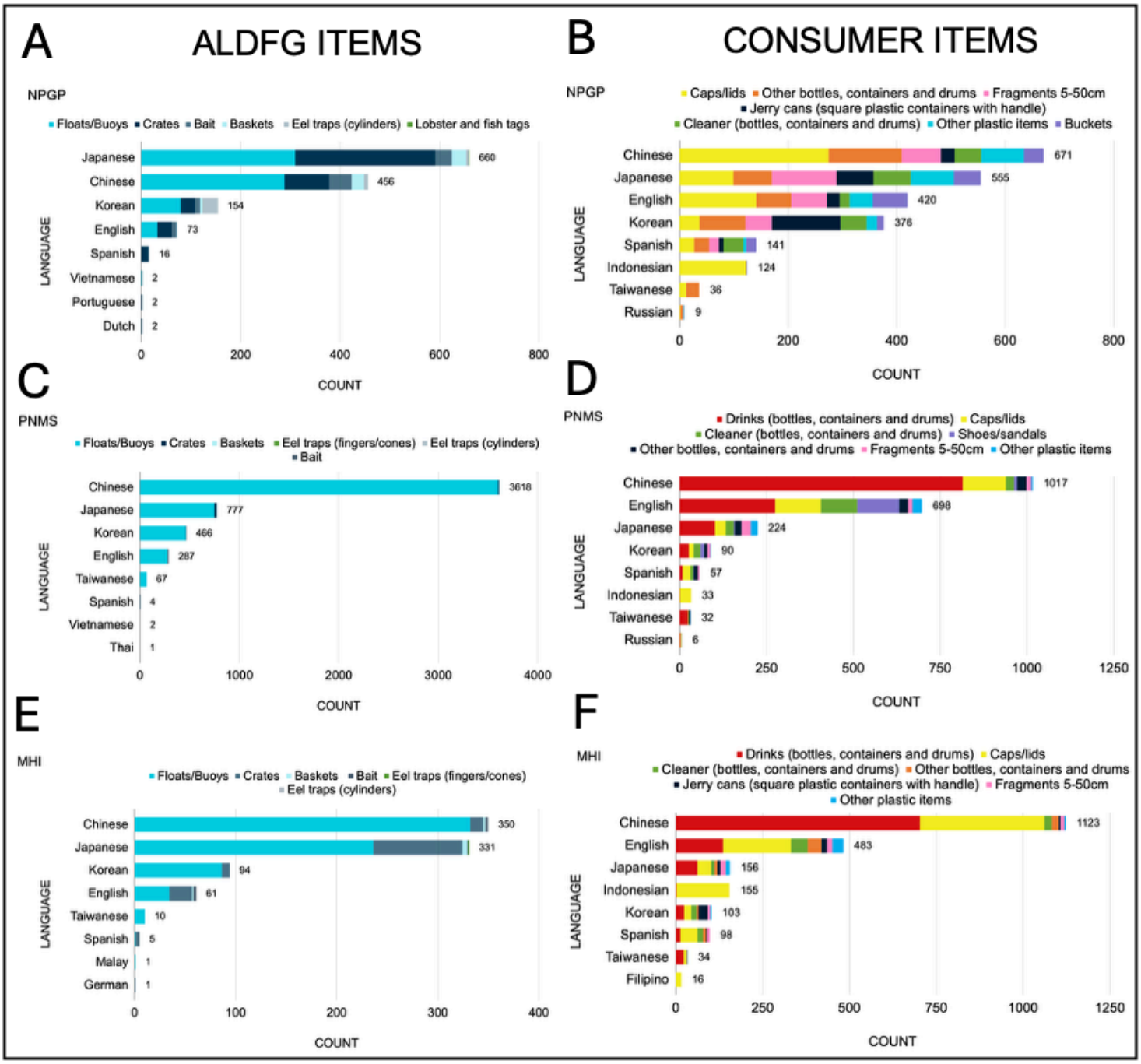


Figure 4

Languages identified on debris collected from the North Pacific Garbage Patch (NPGP; Panels A–B), Papahānaumokuākea National Marine Sanctuary (PNMS; Panels C–D), and the Main Hawaiian Islands (MHI; Panels E–F). A total of 19.768 items were analyzed. The left column (Panels A, C, E) displays the abundance of household and consumer items with identifiable written languages, while the right column (Panels B, D, F) shows the subset of ALDFG fishing-gear hard-plastic items, including crates, baskets, floats and buoys, cylinders for fishing-net repair and bait, and eel traps. Only the top eight languages are shown in each panel; full language lists and counts are provided in the Supplementary Information (SI).

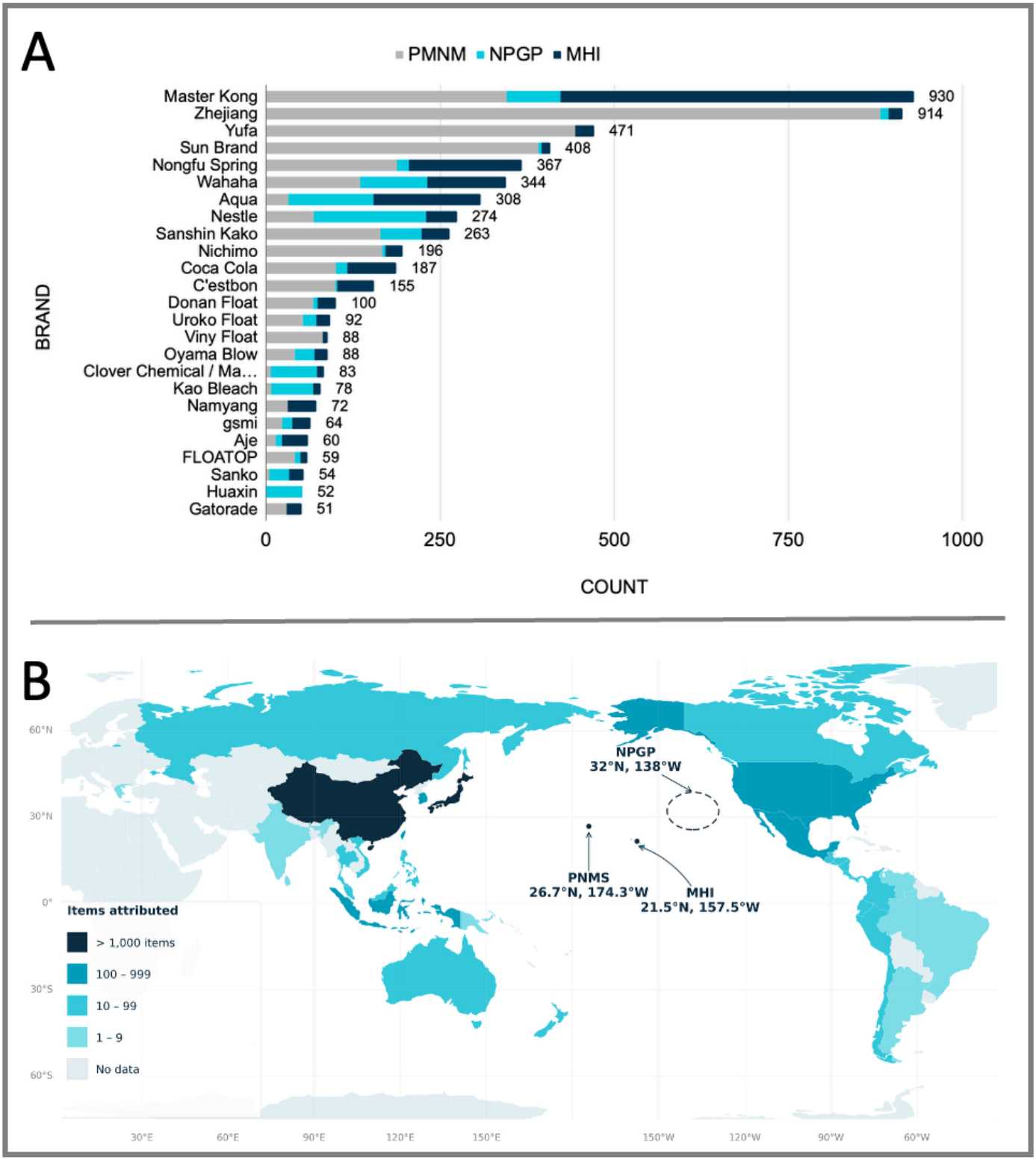


Figure 5

Brand and production country analysis of provenance-marked debris. (A) Distribution of the top 25 brands among 11,327 branded items, representing 5,758 items across the NPGP, PNMS, and MHI; only brands with ≥50 items are shown, with the remainder detailed in the Supplementary Information. A total of 2,594 distinct brands were recorded. Dominant contributors include Chinese float manufacturers (Zhejiang, Yufa, Jxiong Sun Brand), Chinese consumer brands (Master Kong, Nongfu Spring, Wahaha), Japanese float manufacturers (Sanshin Kako, Nichimo), and international brands (Aqua, Nestlé, Coca-Cola). (B) Production countries identified on 6,970 of 19,768 individually examined items, based on written language markings, brand logos, and manufacturing stamps; colour intensity reflects item count per country. China and Japan together account for 75% of attributed items (3,769 and 1,479 items respectively), with South Korea, Indonesia, and the United States forming a secondary tier. Collection sites are indicated by a dashed ellipse (NPGP) and filled circles (PNMS, MHI). Production country reflects the location of manufacture or market distribution and does not necessarily correspond to the nationality of the vessel or fleet responsible for the item's loss at sea.

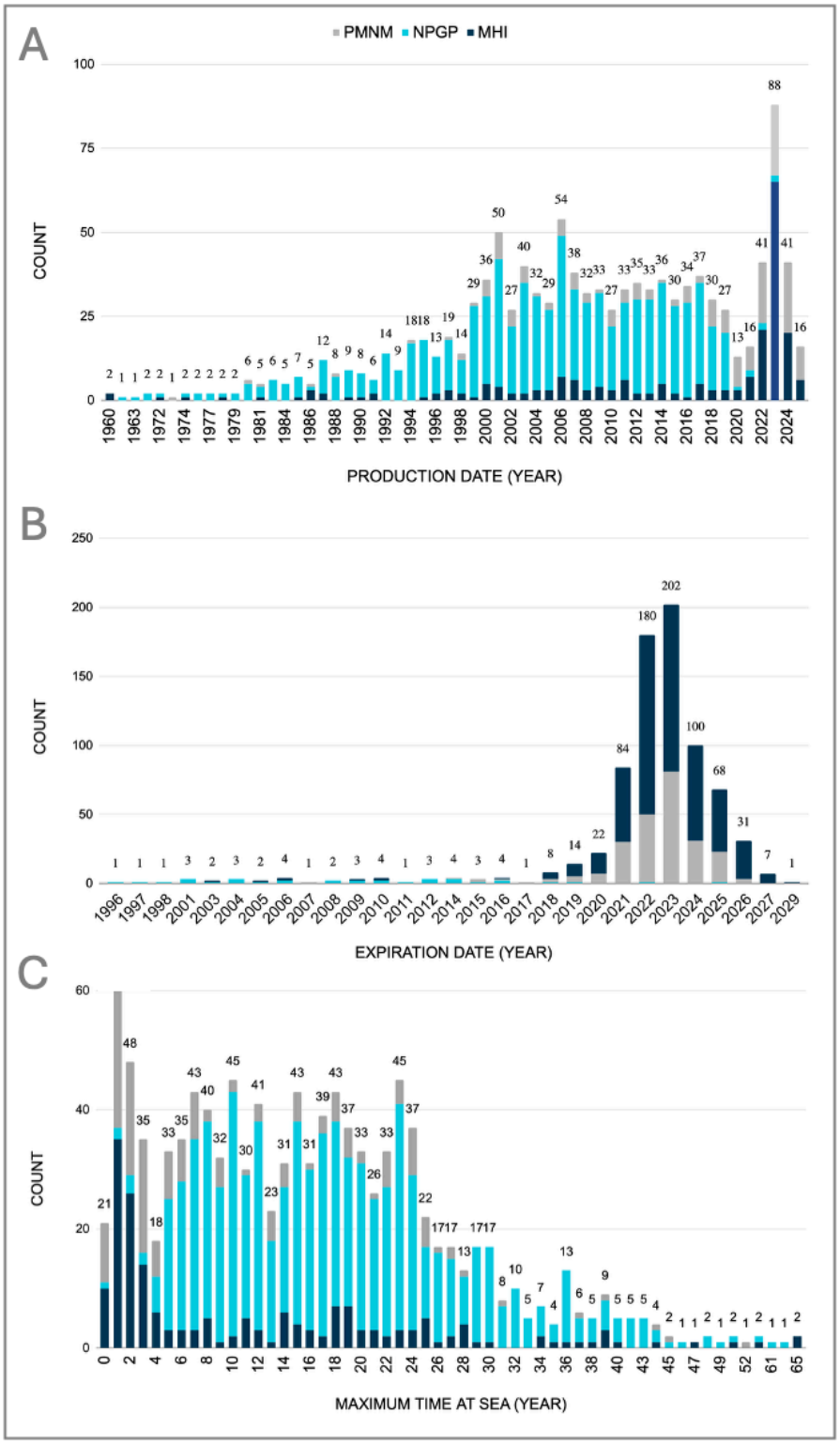


Figure 6

Production dates (Panel A), expiration dates (Panel B), and maximum time spent at sea (Panel C) in year(s) identified on hard plastic debris collected from the Papahānaumokuākea National Marine Sanctuary (PNMS; grey), the Main Hawaiian Islands (MHI; blue), and the North Pacific Garbage Patch (NPGP; cyan). Each panel shows the number of items per year with legible date markings, illustrating the temporal distribution of debris entering and persisting in these three regions. Note that most of the

collected items with production and expirations were recovered between 2023 and 2025. The previous collection years were subsamples of the full dataset, and hence, the dataset was smaller between 2015 and 2022.



Figure 7

Analysis of 174 fishing nets collected from the North Pacific Garbage Patch (NPGP). (A) Distribution of net weight (kg) and surface area, grouped into size classes. (B) Colour distribution of the nets. (C) Morphological characteristics and net configurations, including the number of strands, twist type

(braided, S-twist, or Z-twist), and construction type (knotted or knotless). (D) Number of sides ripped and cut. (E) Estimated time in the marine environment. (F) Pathway of entry into the marine environment.

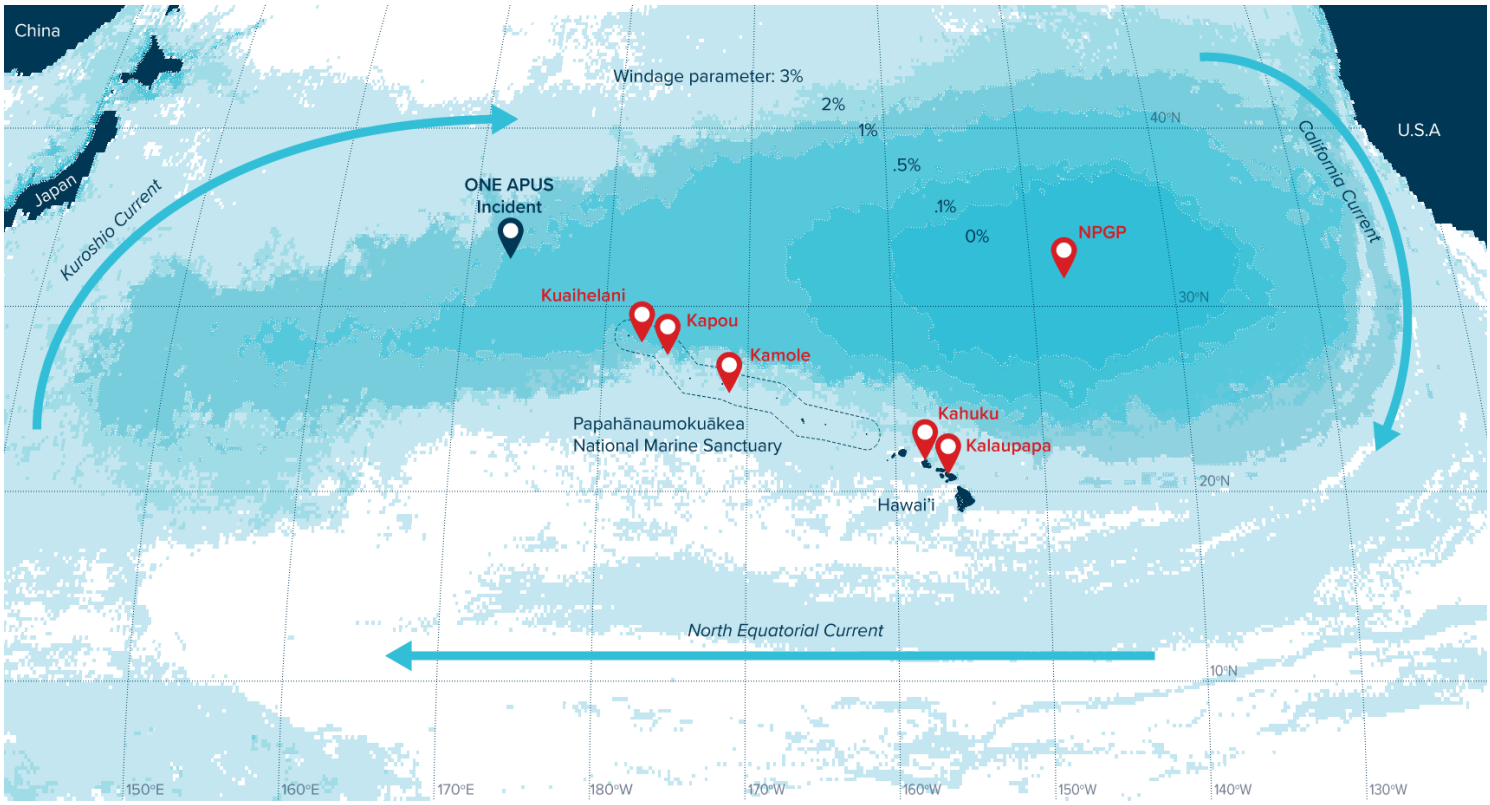


Figure 8

Schematic map of the North Pacific illustrating the influence of windage on the transport and accumulation of floating plastic debris across the three study regions. Contour lines represent windage parameter values (0–3%), indicating the relative contribution of wind forcing to debris drift trajectories, adapted from Lebreton et al. (2018). Items with low windage, such as submerged or dense debris, accumulate preferentially within the North Pacific Garbage Patch (NPGP), while items with higher windage, including capped PET bottles and spherical floats and buoys, are progressively deflected toward downstream island environments. The Papahānaumokuākea National Marine Sanctuary (PNMS; Kuaihelani/Pihemanu (Midway Atoll), Kamole/Kauō (Laysan), and Kapou/Papa□āpoho (Lisianski) Islands) and the Main Hawaiian Islands (MHI; Kahuku and Kalaupapa) are positioned along major current pathways downstream of the NPGP and act as interception zones for high-windage floating debris. The location of the ONE APUS container spill (30 November 2020; 33°04'N, 172°52'E) is also shown, approximately 1,600 nautical miles northwest of Hawaii. The higher proportional recovery of spill-derived items at PNMS and MHI sites relative to the NPGP reflects the geographic proximity of the spill location to the Hawaiian archipelago and wind-driven transport toward island shorelines rather than gyre-mediated accumulation.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- RoyeretalcatchanalysisSI2026.docx
- Table1.docx