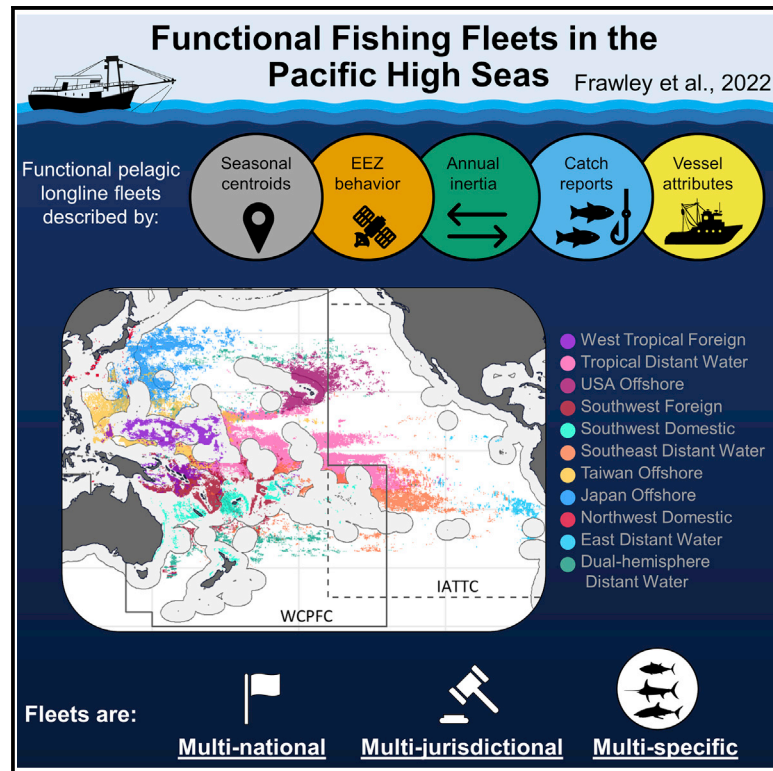


Clustering of disaggregated fisheries data reveals functional longline fleets across the Pacific

Graphical abstract



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In brief

This study relies on the integration of disparate public data sources to delineate and describe pelagic longline fisheries across the Pacific, often considered among the least transparent seafood production systems worldwide. The analysis here reveals a diverse sector in the midst of transition, highlights gaps in the scope and scale of existing monitoring efforts, and emphasizes how explicit consideration of distinct vessel behaviors and attributes can be used to target and modernize sustainable fisheries management approaches.

Highlights

- Despite their value and ocean impacts, many longline fisheries remain opaque
- Using public data sources, we characterize 11 distinct fishing fleets across the Pacific
- Our integrated analyses highlight current gaps in monitoring and management
- Consideration of unique vessel behaviors and attributes can help target policy



Article

Clustering of disaggregated fisheries data reveals functional longline fleets across the Pacific

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<https://doi.org/10.1016/j.oneear.2022.08.006>

SCIENCE FOR SOCIETY With improvements in technology, big ocean data are increasingly used to describe ocean uses and prioritize management action. Within fisheries, much of the discourse to date has concerned the identification of flag states responsible for illegal fishing and/or interactions with protected species. Yet, little guidance exists regarding how recent advances can be leveraged to inform the development of sustainable and equitable harvest-control rules. Here we link vessel movement and registration data with catch reports to characterize “functional fishing fleets” across the Pacific. Considering the strengths and limitations of each data source, we argue they are more valuable when used collectively to support the evolution of existing management operations than as the sum of their parts deployed in isolation. Indeed, the future sustainability of high seas fisheries may hinge on increased cooperation and transparency required to harness and democratize the benefits of the digital ocean ecosystem for improved governance.

SUMMARY

Ensuring the long-term sustainability of tuna, billfish, and other transboundary fisheries resources begins with data on the status of stocks, as well as information concerning who catches what fish, when, where, and how. Despite recent improvements in fisheries monitoring and surveillance, such dynamics remain poorly understood across the high seas. Here we delineate and describe pelagic longline activity in the Pacific Ocean using a framework that integrates descriptive vessel information and tracking data with species-specific catch reports. When parsed by distinct vessel behaviors and attributes, disaggregated fisheries data highlight the existence of multi-national, multi-specific (i.e., targeting multiple species) fishing fleets, many of which target waters that span more than one management area. Our findings emphasize the need for increased coordination across regional and sub-regional governance bodies and suggest that effective and equitable management of the sector may require efforts to move beyond single-species, single-area controls and operational distinctions based primarily on vessel flag and/or gear type alone.

INTRODUCTION

Across the Pacific Ocean, tuna, billfish, and other highly migratory species are an important source of livelihoods and food se-

curity for both developed and developing countries.¹ Pacific tuna and billfish fisheries, including both industrial high seas fishing operations and ubiquitous small-scale domestic and subsistence sectors, represent ~70% of the global commercial catch



Box 1. Management context

The primary institutions with a mandate to manage transboundary fisheries are Regional Fisheries Management Organizations (RFMOs). Across the Pacific Ocean, many tuna and billfish species span the jurisdictions of the Inter-American Tropical Tuna Commission (IATTC; Eastern Pacific) and the Western and Central Pacific Fisheries Commission (WCPFC). While the IATTC was established in 1949, the WCPFC is a far younger organization, which was formed in 2004 following the entry into force of the UN Fish Stocks Agreement (UN 1995). Over the past several decades, both RFMOs have adopted a number of conservation and management measures designed to manage tuna fisheries through limits on catch, fishing effort, and capacity, as well as the establishment of closed areas, fishing seasons, and gear restrictions.^{20,21} Simultaneously, sub-regional bodies (i.e., the Pacific Islands Forum Fisheries Agency [FFA] and the Parties to the Nauru Agreement [PNA]) have implemented their own cooperative controls for fisheries operating within their exclusive economic zones (EEZs). Notably, sub-regional efforts to enhance fisheries MCS have resulted in a requirement mandating that, to be placed in good standing, all foreign fishing vessels operating within Pacific Island EEZs must utilize VMSs and AISs. Because of this and other development and management measures that have been applied to regional purse seine fisheries (i.e., the PNA Vessel Day Scheme), licensing revenue and other associated fisheries economic benefits have increased substantially for western and central PICs over the past decade.²² In contrast, the management of pelagic longline fisheries has progressed at a much slower pace. Recent resource management and allocation discussions have been shaped by the tensions between PICs wishing to maintain sovereign rights over their EEZs and develop their domestic fishing capacity, and many Distant Water (DW) fishing nations that advocate for flag-based measures (i.e., those that would apply equally across territorial waters and the high seas).²⁰ Where longline harvest guidelines are established, most annual limits continue to be negotiated on the basis of historical catch and effort levels as reported by individual nation-states.²¹

of these species.^{2,3} With climate change continuing to acutely impact near-shore marine ecosystems, open ocean (i.e., pelagic) fisheries targeting such species are increasingly recognized for their capacity to support healthy and nutritious diets, marine resource-dependent livelihoods, national economies, and regional trade networks.^{2,4–6} Yet pelagic fishery systems, which operate over large areas that often span multiple jurisdictions and geopolitical boundaries, face unique management challenges, many of which are related to uneven data collection, and inconsistent monitoring and enforcement. Enduring knowledge gaps surrounding the nature and extent of regional resource extraction have contributed to ongoing biodiversity loss⁷ while functioning to undermine the development of sustainable harvest strategies and the provision of social and economic benefits.⁸ As new threats and stressors emerge alongside accelerating global environmental and socioeconomic change,⁹ calls for increased coordination, cooperation, and transparency across the sector have intensified, and the need for equitable and comprehensive ecosystem-based resource management has grown increasingly urgent.^{10,11}

Although high-volume purse-seine fisheries comprise the vast majority of large pelagic fisheries landings across the Pacific, pelagic longline fisheries represent a substantial proportion of total catch value (~30% in the Western Pacific in 2019¹²) while exerting significant top-down pressure on open-ocean ecosystems across the basin.¹³ Despite its economic and ecological importance, the pelagic longline sector remains poorly understood and difficult to manage because of inadequate information concerning catch and bycatch, fishing effort, and vessel distribution^{14,15} and the diverse and (at times) competing priorities of participating nations (Box 1). Although fisheries observers are mandatory for all large-scale tuna purse-seine vessels in the region, substantial variation exists across pelagic longline fisheries, with many fleets failing to meet the 5% minimum coverage rate recommended by regional fisheries management organizations (RFMOs).^{16,17} With persistent uncertainty regarding the distribution and biology of target species³ and the development and

expansion of distant water (DW) fishing operations,¹⁸ pelagic longline fisheries are often considered among the least transparent seafood production systems worldwide.¹⁹

Compared with traditional fisheries-dependent data sources (i.e., logbook and observer data), recent improvements in monitoring, control, and surveillance (MCS) technologies have increased the type, quantity, and resolution of observations available to describe the distribution and dynamics of fishing effort, creating a new frontier of digital ocean governance.²³ In particular, satellite-based vessel tracking systems have gained popularity as a means of monitoring the movements and activities of individual fishing vessels. Vessel Monitoring Systems (VMSs), which transmit vessel positions at set intervals via a closed system, have been mandated for a number of fisheries, jurisdictions, and flag states, yet to date the technology has primarily been used for internal monitoring and enforcement activities rather than scientific research because of confidentiality requirements restricting data sharing and access.^{24,25} In contrast, over the past several years researchers have increasingly relied on public, high-resolution Automatic Identification Systems (AISs) data, originally designed as a real-time collision avoidance tool, to describe and evaluate the behaviors and attributes of fishing vessels across global oceans.^{19,26,27} Although AIS is recognized as an imperfect data source given regional differences in usage and satellite coverage,^{23,28} the technology has been successfully used to identify patterns of transshipment behavior,^{29,30} and port usage;³¹ detect illegal, unreported, and unregulated (IUU) fishing activity;^{32,33} and monitor marine protected area effectiveness.^{34,35}

As the fishing capacity intensifies and ecological impacts accelerate,³⁶ harnessing increased observational power to improve understanding of how fishers allocate their effort in time and space is of critical importance.³⁷ Changes in the spatio-temporal distribution of fishing effort can impact the structure and function of pelagic food webs,³⁸ the economic value of landed seafood products,³⁹ and scientific assessments of sustainable harvest levels.⁴⁰ Although knowledge of how people operate in a fishery system is essential for the development of

equitable and effective management strategies,⁴¹ significant uncertainty persists regarding where fishers choose to fish and why.⁴² Most regulatory regimes continue to be based on a narrow suite of technical parameters (e.g., maximum sustainable yield) and where human dimensions are acknowledged, fishers are often treated as uniform elements with little consideration of heterogeneity in goals, strategies, and scales of operation. Yet, even among fishing vessels using the same gear and operating under the same flag, substantial differences may exist (within and between years) in the selection of fishing tactics, grounds, and target species as different vessel groups respond to unique institutional and economic drivers.^{43–45} Indeed, socio-economic factors rather than environmental ones may be primarily responsible for observed patterns of fishing activity.^{26,46} Because fleet-specific differences in target and non-target species interactions and catch efficiency may have substantial impacts on the population dynamics of pelagic resources,⁴⁷ identifying and accounting for diversity of fishing activity should be a priority for research and management.⁴⁸

Scientific understanding of pelagic fishing fleets and resource dynamics is rapidly improving, yet to date limited efforts have been made to integrate vessel movement data with catch and effort records,^{44,49,50} particularly at the spatial scales relevant to high seas, pelagic longline fishing operations. Despite recent improvements in fisheries MCS, self-reported data concerning the timing and location of fishing activity and the composition of catch continue to be the foundation of scientific tools used to manage and allocate pelagic fisheries resources. However, with incentives to misreport and other responsibilities at sea that can distract fishers from entering complete and accurate data,⁴⁸ a continued and exclusive reliance on such records may be problematic. Although previous AIS investigations have produced valuable insights and garnered significant public interest,^{26,32,51} the potential for AIS data to productively inform existing fisheries management protocols and procedures remains largely untapped.

Here, to address this gap, we introduce a framework and clustering methodology capable of integrating AIS vessel tracking data, descriptive vessel information, and basin-scale catch and effort data. In doing so, we combine top-down (i.e., satellite observations) and bottom-up (i.e., self-reported) fishery-dependent data sources and demonstrate their collective potential to contribute more than the sum of their individual parts in advancing a synoptic view of pelagic longline fishing activity across the Pacific Ocean. Through the application of a regional, fleet-specific approach, we rely on observed patterns and behaviors and previous management reports to identify unique operational strategies, highlighting distinct socio-economic drivers, ecological impacts, and management opportunities as they manifest across the broad geographic scope of pelagic longline fisheries in the Pacific. Although limited by the resolution and completeness of available data, our results highlight the utility of disaggregated fisheries analysis and the potential benefits of a holistic, basin-scale, ecosystem-based fisheries management approach. Indeed, we argue that such an approach is urgently required to address emerging threats and historical deficiencies, and to ensure the sustainability of Pacific tuna and billfish resources for future generations.

RESULTS

Historical trends in catch and effort

The distribution, target species, and intensity of pelagic longline fishing catch and effort across the Pacific Ocean have changed substantially over the past several decades (Figure 1). In the Western Pacific Ocean (WPO), total longline vessel numbers have slowly declined over the past 15 years from a peak of more than 5,000 vessels in the early 1990s to an estimated 1,672 active fishing vessels operating in 2019.¹² Historical time-series data for Eastern Pacific Ocean (EPO) vessel participation are not available. During the same time, total fishing effort has increased across the Pacific Ocean from ~550 million hooks in 1995 to ~850 million hooks in 2019 (down from a peak of ~950 million hooks in 2012; Figure S1). Increases in fishing intensity (i.e., number of hooks) are not uniformly distributed, while effort in the eastern and western tropics has decreased alongside declines in catch per unit effort (CPUE) of Yellowfin (*Thunnus albacares*) and Bigeye (*T. obesus*) tuna, notable increases are evident in the central tropics and in the sub-tropical south Pacific alongside the recent development of Pacific Island Countries' (PICs) domestic longline fleets and the growth of DW fishery operations targeting South Pacific albacore (*T. alalunga*) (Figure 1).^{6,52}

Sample population of observed vessels

Using AIS data, we observed 2,471 vessels identified as using pelagic (i.e., “drifting”) longline gear fishing within the combined convention area of the Inter-American Tropical Tuna Commission (IATTC) and Western and Central Pacific Fisheries Commission (WCPFC) from 2017 to 2019. The dominant nations comprising this sample were Taiwan (30.0%), Japan (22.9%), China (21.4%), the United States (7.3%), and Korea (4.6%). As others have noted,²⁸ AIS data should not be considered representative of total longline fishing effort because AIS usage is most common among (1) large vessels (i.e., >24 m), (2) upper- and middle-income countries/territories, and (3) DW fleets. A comparison of our observed sample with recent Regional Fishery Management Organization (RFMO) longline registries reveals a lack of concordance between the two datasets (Figure 2A). Although quantitative comparisons are challenging given that vessels not actively fishing may be listed in such registries, discrepancies appear most pronounced in the IATTC region, where AIS usage among Central and Southern American near-coastal and/or small-vessel pelagic longline fleets is limited, as exemplified by substantially more registered than observed vessels flagged to Panama and Costa Rica in 2019 (Figure 2B).²⁸ A comparison of the registered lengths of vessels listed by the IATTC and the WCPFC (Figure S2) suggests that differential adoption of AIS technology may not strictly be linked with differences in median vessel size across the two management areas²⁸ and may in part be driven by different regulatory and/or reporting requirements. In conjunction with low AIS usage, many Central and South American longline fishing nations do not publicly release gridded longline catch and effort data (as is the case with several developing Western Pacific nations that additionally do not register vessels internationally; see legend for Figure 2B) and may not be identified individually in annual IATTC fishery reports and/or summary statistics. Considering observations from 2019 only, AIS data included 630 vessels operating in the

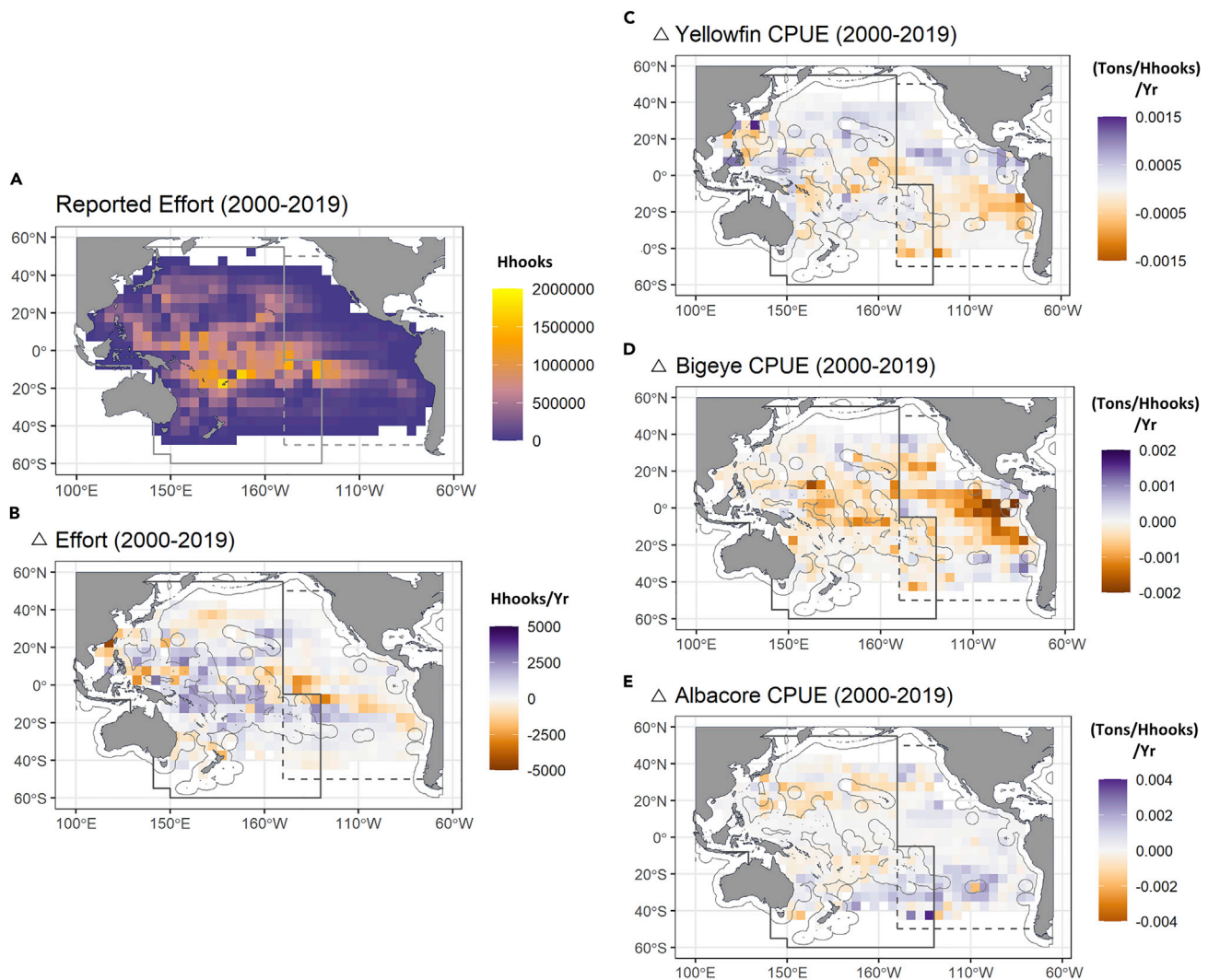


Figure 1. Historical changes in Pacific longline catch and effort

(A–E) These panels depict the evolution of pelagic longline fishing effort in hundred hooks (Hhooks) and catch per unit effort (CPUE; shown in tons per Hhook) for select tuna species over the past two decades as reported by Regional Fisheries Management Organizations (RFMOs) in each $5 \times 5^\circ$ grid cell. Values show in (A) represent total number of hooks reported in each cell between 2000 and 2019, while Δ (rate of change) values shown in (B) (Δ in fishing effort in Hhooks/year), (C) (Δ Yellowfin CPUE in tons/Hhooks/year), (D) (Δ Bigeye CPUE), and (E) (Δ Albacore CPUE) were obtained via simple linear regression models calculated for each cell (i.e., year used as the predictor variable and Δ representing the resulting slope). Only cells with >5 years of data are presented in the analysis. RFMO boundaries are delineated by solid (Western and Central Pacific Fisheries Commission [WCPFC]) and dashed (Inter-American Tropical Tuna Commission [IATTC]) black lines.

IATTC (as compared with 2,393 registered vessels), 2,014 vessels operating in the WCPFC (as compared with 2,651 registered vessels), and 532 vessels operating across jurisdictions (as compared with 1,112 dual-registered vessels; Figure 2A).

Fleet clustering

The vessel clustering algorithm indicated that observed vessels were optimally partitioned into 11 fleet clusters as based on seasonal center of gravities (COG), inertia (i.e., range), exclusive economic zone (EEZ) behavior, estimated species overlap (i.e., co-occurrence in time in space with gridded catch totals reported by RFMOs), and vessel characteristics (Figure 3). A more complete description of data inputs, clustering proced-

ures, and naming conventions can be found in the [experimental procedures](#). With the exception of the East Tropical DW cluster (which appeared in 2017) and the East DW cluster (which emerged in 2018 and 2019), the composition and characteristics of these clusters were largely consistent across the 3 years of the study period (Figure 4A), despite differences in the number of vessels being clustered because of progressively increasing AIS coverage. Vessel exchange between clusters across years (Figure 4B) was greatest between those clusters that were weakly defined (large intracluster distance) and closely related (small intercluster distance) (Figure 4A). Within the WPO, there was substantial exchange between the West Tropical Foreign fleet and the Taiwan Offshore fleet ($n = 51$ vessels), and between

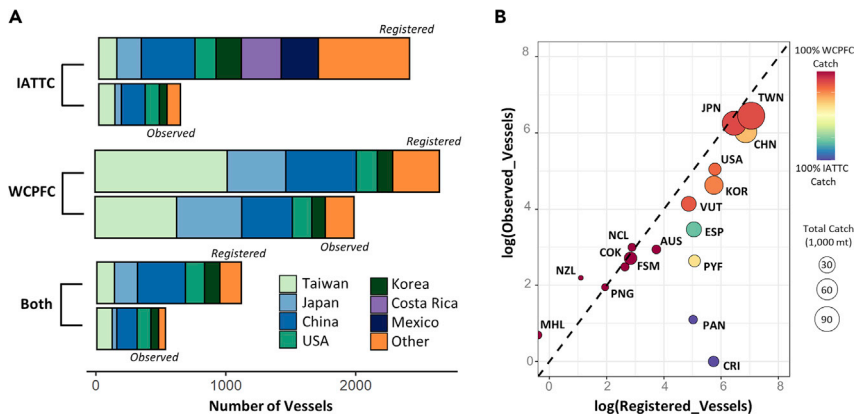


Figure 2. Regional differences in observed and registered longline vessels

(A) Comparison of registered (upper) and observed (lower) vessels by Regional Fishery Management Organization (RFMO) jurisdiction across the Pacific Ocean. Registered vessels were obtained from recent lists maintained by the WCPFC and IATTC, while observed vessels were assessed using Automatic Identification System (AIS) fishing activity data from 2019. Both refer to those vessels listed in each RFMO registry or observed operating within both WCPFC and IATTC jurisdictions.

(B) Comparison of observed and uniquely registered vessels by flag state across the combined convention bounds of the IATTC and WCPFC. Points are sized according to total 2019 longline catch (i.e., the sum of longline landings (mt) presented in the 2019

WCPFC Fishery Yearbook and the 2019 longline values presented in IATTC Total Estimated Catch database) and are colored by the percentage of landings derived from each RFMO area. The dotted line denotes values where registered and observed vessels are equal. Note that the scatterplot is limited to the 25 flag states associated with the largest total catches in the aforementioned data sources while excluding countries that reported landings in the absence of >1 registered or observed fishing vessel (i.e., Indonesia, Vietnam, Solomon Islands, Palau, Kiribati, and Western Samoa).

the Taiwan Offshore fleet and the Japan Offshore fleet ($n = 74$ vessels). In the EPO there was substantial exchange between the Tropical and East Tropical fleets ($n = 101$), the Tropical and Southeast DW fleets ($n = 48$), and the East Tropical and Southeast DW fleets ($n = 70$). Although fleets were distributed across the Pacific Basin, the majority of fleet effort and diversity was concentrated in the WPO between 20° S and 20° N (Figure 4C). A relative comparison of the clustering inputs (normalized to facilitate comparison between variables and across scales) associated with different fishing fleets can be found in Figure 5, while more detailed descriptions of specific fleets and regions (as grouped by target species) can be found in the sections below.

Western and Central Pacific yellowfin and bigeye

The West Tropical Foreign fleet is dominated by medium vessels (180.5 ± 135.4 gross registered tons [GRTs]) from China, Taiwan, and Japan that operate in the EEZs of the Marshall Islands, the Solomon Islands, and the Federated States of Micronesia alongside a growing number of domestic vessels (Figure 4C). Many of these vessels traditionally used shallow-set gear to target yellowfin (Figure 5A), but following declines in CPUE of that species in the 1980s and 1990s and the development and proliferation of deep-set fishing gear, increased effort has been directed toward bigeye.^{53,54} In addition to paying license fees to access PIC territorial waters, in recent years the practice of “chartering” has allowed many DW fishing nations to secure additional bigeye quota while operating under PIC flags.⁶ This fleet is composed of a mixture of ice and freezer vessels, most of which, regardless of flag, are based out of PIC ports. Although bigeye and yellowfin destined for sashimi markets are the primary targets (Figure S3A), “other” species (see experimental procedures) caught as bycatch are sold more locally. In contrast, the Tropical DW fleet is composed of large, bigeye targeting vessels (539.1 ± 112.7 GRTs; Figure S3B) from Korea, China, Taiwan, and Japan that operate over a wide geographic range on the high seas, as observed in both the IATTC and WCPFC convention areas (Figure 4C). These vessels increasingly rely on carrier vessels to reduce operating costs, resupplying fuel and bait, and transship-

ping catch at sea during the 18–24 months between port visits.⁶ Among the fleets principally overlapping with bigeye and/or yellowfin, only the small-vessel (87.1 ± 32.2 GRTs) USA Offshore fleet is primarily composed of domestically based vessels (Figures 4C and 6A). Traditionally, deep-set fishing operations targeting bigeye in waters to the southwest and northwest of Hawaii comprised the majority of this fleet’s catch and effort, with a smaller portion of the fleet using shallow-set gear to target swordfish in more temperate waters, although in recent years both fisheries have expanded to the northeast.⁵⁵

South Pacific albacore

Three distinct fleets primarily overlapped with South Pacific albacore grounds in sub-tropical and temperate waters (Figures 4C and 5A). Operating within national jurisdictions, the Southwest Foreign fleet (Figure S3C) is dominated by medium-sized vessels (206.1 ± 102.2 GRTs) from Taiwan and China that are licensed to fish in the territorial waters of South Pacific Island nations, while the adjacent and overlapping Southwest Domestic fleet (Figure S3D) is composed of small vessels (105.4 ± 37.1 GRTs) from Fiji, New Caledonia, and other PICs, as well as Australia and New Zealand, operating in domestic waters. Asian longline fleets from Taiwan and China historically landed the most South Pacific albacore, but the relative proportion of PIC catch has increased in the past several decades⁵² as the assertion of territorial rights has facilitated increased investment in domestic fisheries.⁵⁶ High seas operations are dominated by the Southeast DW fleet composed of large vessels (378.54 ± 155.97 GRTs) from China and Taiwan. In recent years, overlap and exchange between such vessels and adjacent DW (namely, East Tropical DW and Tropical DW) fleets targeting bigeye has likely increased as a number are believed to switch targets within and between years (Figure 4B).⁶ Indeed, this fleet’s bimodal distributions of annual estimated overlap with albacore and bigeye (Figure 6B) suggest that, as currently defined, it may include a small number of vessels primarily targeting bigeye. All three South Pacific albacore fleets primarily service markets for canned tuna, although some of the more modern vessels are equipped with deep freezing capabilities designed to take

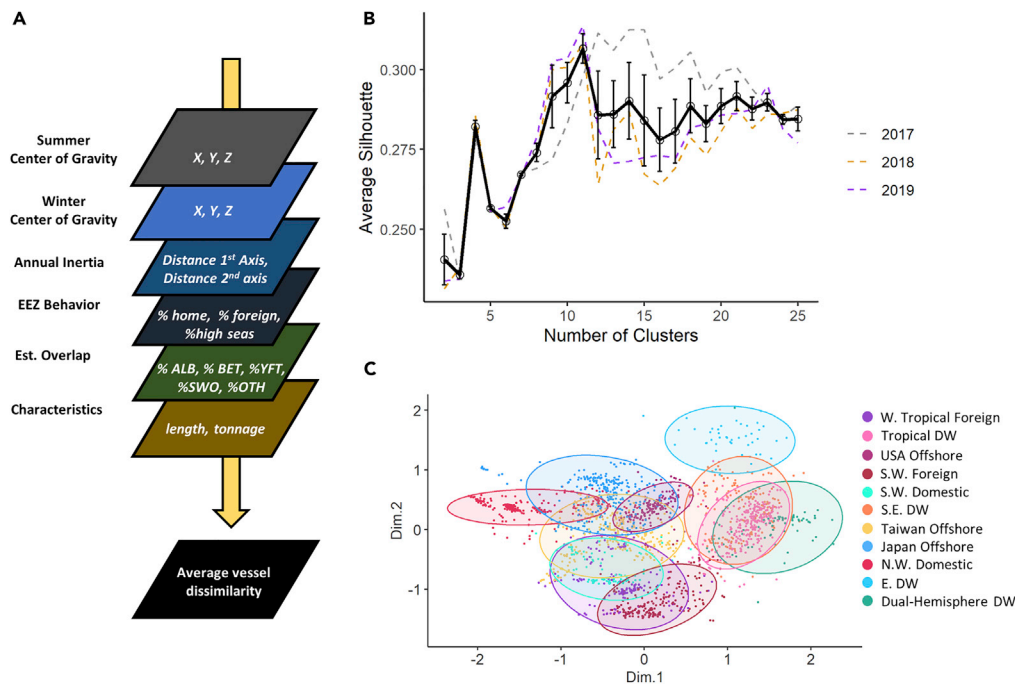


Figure 3. Vessel clustering procedure and outputs

(A) Schematic of clustering methodology. Inputs within each annual layer were scaled prior to dissimilarity calculations. If a vessel was missing data for a particular layer, the average dissimilarity across all vessels for that layer was used in its place. The estimated overlap layer was calculated using catch reports documenting gridded landings of albacore tuna (ALB), bigeye tuna (BET), yellowfin tuna (YFT), swordfish (SWO), and other species (OTH).

(B) Optimal number of clusters ($n = 11$) estimated by Partitioning Around Medoids (PAM) clustering algorithm and averaging across the 3 years of the study period (\pm SD).

(C) Sample cluster output obtained using 2018 data; cluster ellipses were drawn at the 90% confidence level following the application of multi-dimensional scaling to reduce observed vessel differences to two dimensions.

advantage of an emerging Japanese market for low-temperature sashimi-grade albacore.⁶

Northwest Pacific multi-species

The Taiwan Offshore longline fishing fleet (sometimes referred to as a “small-vessel” or “coastal” fleet) is considered more itinerant than other regional fleets and is known to switch target species based on resource availability and access conditions.^{6,57} These vessels were observed operating in diverse jurisdictions, as well as the high seas (Figure 4C). Some operate out of ports in Taiwan, but many others are based in Micronesia, Guam, and the Philippines.¹² A majority of these small vessels (61.5 ± 26.9 GRTs) make short (i.e., 7–10 days) trips to target yellowfin and/or bigeye tuna for fresh sashimi markets,^{6,58} consistent with their high overlap with these species (Figure 5A). Some vessels from this fleet may also engage in the seasonal harvest of “other” species, like Pacific bluefin tuna (*T. orientalis*), billfish, and shark.^{59–61} Among observed vessels, overlap with other species peaked during March and April, while overlap with yellowfin was most pronounced from July to January (Figure 6C). Although our analysis did not reveal a positive association with albacore catch (Figure 5A), others have reported that the distinction between this fleet and adjacent fleets has become less pronounced as declines in CPUE of traditionally important species have prompted many smaller vessels to begin targeting albacore in more distant waters.^{6,52}

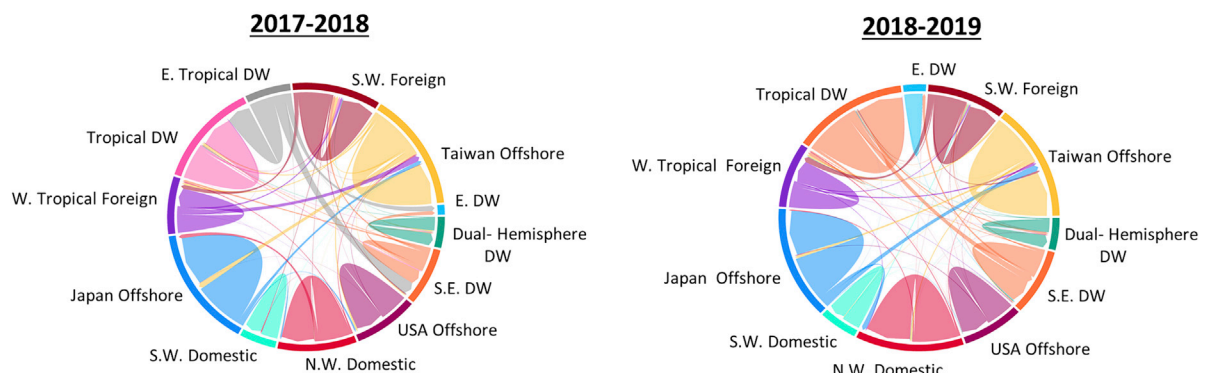
Two other small vessel fleets, the Japanese Offshore fleet (48.3 ± 42.2 GRTs) and the near-coastal Northwest Domestic (88.9 ± 147.7 GRTs) fleet, target sub-tropical and temperate waters farther north in the highly productive Kuroshio-Oyashio current system (Figure 4C).⁶² Both groups of vessels are primarily active during the first two-quarters of the year traditionally used to target albacore (January–March) and bluefin (April–June) in waters off the southeast and southwest coast of Japan, with smaller numbers of vessels additionally targeting yellowfin and bigeye during the summer and fall.^{63–65} At more temperate latitudes, activity is dominated by Japanese Offshore vessels using shallow-set fishing gear to target swordfish (*Xiphus gladius*) and other species like blue shark (*Prionace glauca*) (Figure 5A).⁶⁶ The targeting of blue sharks has increased since the late 1990s as effort is believed to have shifted northeast.⁶⁷

Poor data coverage contributes to the difficulty in resolving nuances within and across Northwest Pacific pelagic longline fishing fleets. Irrespective of the waters in which they operate, many domestically based Taiwanese and Japanese vessels are considered part of small-scale fleets (as defined by gross tonnage), which are not obligated to release gridded catch and effort data publicly. Omitted records associated with the “OD” (i.e., domestically based, offshore) Taiwanese fleet and the “CS” (i.e., domestically based, coastal) Japanese fleet, as identified and reported in the WCPFC Tuna Fishery Yearbook,⁶⁸ comprised 18.3% and 61.7% of each respective nation’s total

A

| | Name | Intracluster Distance (average diameter) | Intracluster Distance (complete diameter) | Cluster Size | Intercluster Distance | Years | Fleet Size | Fleet Composition |
|---|-----------------------|--|---|----------------|---|-------|------------|----------------------|
| ● | West Tropical Foreign | 0.592 (± 0.06) | 3.10 (± 0.10) | 159 (± 36.3) | S.W. Foreign (1.52 ± 0.05), Taiwan Offshore (1.70 ± 0.05) | 3 | 124 | 33.4% CHN, 25.0% TWN |
| ● | Tropical DW | 0.49 (± 0.01) | 2.61 (± 0.30) | 230 (± 57.8) | E. Trop. DW (1.58), USA Offshore (1.63 ± 0.02) | 3 | 261 | 36.7% KOR, 29.8% CHN |
| ● | USA Offshore | 0.34 (± 0.02) | 2.19 (± 0.09) | 144 (± 11.4) | Japan Offshore (1.46 ± 0.07), Taiwan Offshore (1.60 ± 0.02) | 3 | 141 | 99.2% USA, 0.7% TWN |
| ● | East Tropical DW | 0.577 | 3.08 | 194.00 | Tropical DW (1.58), S.E. DW (1.76) | 1 | NA | 26.2% CHN, 25.2% JPN |
| ● | Southwest Foreign | 0.49 (± 0.06) | 2.98 (± 0.30) | 195 (± 16.5) | W. Trop. Foreign (1.52 ± 0.05), S.W. Domestic (1.56 ± 0.07) | 3 | 180 | 60.5% CHN, 12.5% TWN |
| ● | Southwest Domestic | 0.438 (± 0.01) | 2.22 (± 0.16) | 91.7 (± 16.0) | S.W. Foreign (1.56 ± 0.07), N.W. Domestic (1.95 ± 0.01) | 3 | 87 | 25.2% FJI, 20.6% NCL |
| ● | Southeast DW | 0.673 (± 0.03) | 3.24 (± 0.57) | 156.7 (± 40.2) | Trop. DW (1.75 ± 0.19), E. Trop. DW (1.76) | 3 | 122 | 63.1% CHN, 20.5% TWN |
| ● | Taiwan Offshore | 0.507 (± 0.02) | 2.51 (± 0.04) | 273.7 (± 16.1) | Japan Offshore (1.42 ± 0.11), USA Offshore (1.60 ± 0.02) | 3 | 270 | 77.7% TWN, 12.6% JPN |
| ● | Japan Offshore | 0.485 (± 0.04) | 2.50 (± 0.36) | 252 (± 14.7) | Taiwan Offshore (1.42 ± 0.11), USA Offshore (1.46 ± 0.07) | 3 | 241 | 69.7% JPN, 29.8% TWN |
| ● | Northwest Domestic | 0.556 (± 0.03) | 3.26 (± 0.19) | 284.3 (± 72.5) | Japan Offshore (1.87 ± 0.05), Taiwan Offshore (1.94 ± 0.11) | 3 | 254 | 55.5% JPN, 37.7% TWN |
| ● | East DW | 0.585 (± 0.12) | 3.14 (± 1.31) | 56.5 (± 16.2) | S.E. DW (2.05 ± 0.09), Trop. DW (2.55 ± 0.09) | 2 | 40 | 65.0% ESP, 15.0% JPN |
| ● | Dual-Hemisphere DW | 0.535 (± 0.03) | 3.27 (± 0.75) | 66.3 (± 15.5) | Trop. DW (1.92 ± 0.08), S.E. DW (2.03 ± 0.07) | 3 | 61 | 42.6% TWN, 31.1% VUT |

B



C

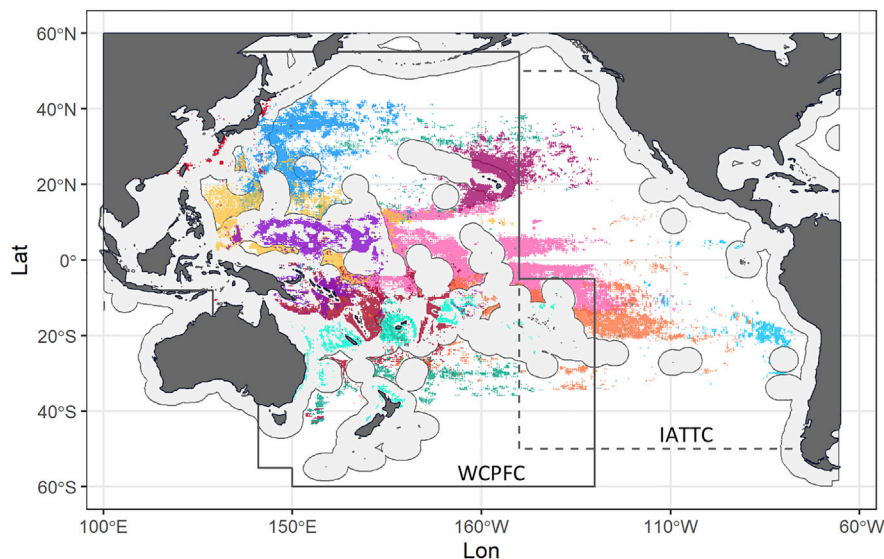


Figure 4. Characteristics, connectivity, and spatial distribution of identified clusters

(A) Breakdown of identified clusters, characteristics, and validation metrics used to subsequently identify and characterize fishing fleets. Values presented in columns 2–5 represent means (±SD) of metrics calculated annually. Although 11 clusters were identified each year, the East Tropical Distant Water (DW) cluster

(legend continued on next page)

WCPFC tuna and billfish landings in 2019. As such, it is unsurprising that comparatively more effort was observed (via AISs) across the Northwest Pacific during our study period than would be expected based on the number of hooks reported in non-confidential gridded catch and effort reports furnished by the WCPFC (Figure S4), although our power of inference is limited by unquantified differences in satellite coverage and gear usage (i.e., variation in the number of hooks per basket used per longline set). With both the Japanese Offshore and Northwest Domestic fleets identified in our analysis composed of vessels observed across broad latitudinal ranges with low inertia, variable species loadings (Figures S3E and S3F), and mixed flag associations, it is possible that both groups are composed of sub-fleets that we were unable to resolve with currently available public data.

Other fishing fleets of interest

Among Pacific Ocean pelagic longline fleets, the Eastern DW fleet dominated by large vessels from Spain (436.4 ± 148.63 GRTs) has emerged perhaps the most recently.¹² This fleet is known to rely on shallow-set gear to land swordfish (Figures 5A and S3G) and other species, such as blue shark, brown shark (*Carcharhinus plumbeus*), and marlin (*Istiophoridae* sp.). Scarce information exists regarding the catch, relative abundance, and biological parameters of many such species,^{69,70} as is emphasized by their lack of regional representation in many of the gridded catch reports used for this analysis (Figure S3G). Likewise, the activities of the Dual-Hemisphere DW fleet remain incompletely documented. This fleet is dominated by large vessels (500.9 ± 149.1 GRTs) flagged to Taiwan and Vanuatu, a pair of nations between whom “flags-of-convenience” relationships are common,⁶ as well as a small number of Chinese⁷¹ and Japanese vessels. These vessels were observed overlapping with albacore fishing grounds in the temperate South Pacific during the austral fall and winter (April–September) months and albacore fishing grounds in the temperate North Pacific during the boreal fall and winter (October–March) months (Figure 6D). Although others have noted albacore fishing activity in both locations,^{72–74} to our knowledge, this study presents the first evidence that many of the same vessels fish in both hemispheres (Figure 4C). This fleet, operating at the latitudinal extremes of our study area (Figure 4C), is believed to be primarily targeting juvenile albacore (Figure 6D)⁷⁵ and is reported to employ diverse gear configurations.⁷⁶

DISCUSSION

As the quantity, quality, and availability of fisheries data continue to increase across the pelagic longline sector, synthetic frameworks are needed to productively inform resource management and allocation. Despite progressive declines in biomass and CPUE for a number of important stocks, existing catch reduction agreements are not universally applied, nor agreed to, and debate continues regarding the relative distribution of associated costs and benefits

among participating countries.^{21,77} Here we demonstrate how vessel tracking data can be integrated with descriptive vessel information and catch reports to define relevant management units, estimate target and non-target species interactions, and identify patterns of behavior associated with distinct socioeconomic drivers and ecological impacts. Indeed, our analysis reveals a diverse sector in the midst of transition. Rather than existing as a monolith, Pacific Ocean pelagic longline vessels exhibit considerable differences with respect to fishing strategies, tactics, and scales of operation. These differences are key to understanding not only current activities and impacts but also in evaluating how exposure, sensitivity, and adaptive capacity may vary across fishing fleets in the future with respect to management intervention, environmental change, and/or other emerging challenges. If existing management regimes are to move beyond single-species, revenue-maximizing approaches to broader initiatives that prioritize ecosystem health, sustainable development, and human well-being,⁷⁸ we argue that recognizing and accounting for such heterogeneity will be of critical importance. In adopting an integrative basin-scale approach to examine this marine social-ecological system, we hope to inspire reflection by scholars and practitioners concerning how the functions of existing governmental and non-governmental bodies could be integrated and/or recast to standardize fisheries monitoring and data collection, improve transparency and accessibility, and sharpen analytical precision across the observed scale of regional resource extraction.

Demographic and operational change in longline fisheries

Sustainable management of the pelagic longline sector requires not only an understanding of current conditions and operations but also an acknowledgment of how such dynamics are shaped by historical context, as well as an appreciation of those trends and trajectories likely to shape the future. Recent changes in the number and operation of Pacific longline DW fishing vessels vary by fleet and nation. Over the past several decades, Korea and Japan have reduced the number of active, flagged vessels as declining catch rates, changing food supply policy, and increasing fuel and labor costs have led to policies designed to reduce investment in the fishing industry and restrict the construction of new vessels.⁶ Although Taiwan has also enacted regulations to halt the construction of new vessels, historically such policy functioned to increase the purchase of foreign vessels and incentivize flags of convenience arrangements rather than to reduce fishing effort.⁷⁹ Over the past decade, the Taiwanese government has responded to concerns of overcapacity and insufficient fisheries MCSs by making longline fisheries reform a policy priority, initiating substantive efforts to retire existing vessels and strengthen national institutions and regulations.⁸⁰ Across active Taiwanese fleets, data coverage and completeness are expected to increase in the coming years as e-logbooks and VMS transponders are increasingly mandated

appeared only in 2017, while the East DW cluster emerged in 2018 and 2019. Note that only the two most dominant flag states are listed in the “Fleet Composition” column.

(B) Chord diagrams used to illustrate the flows of vessels between clusters between 2017–2018 and 2018–2019.

(C) Spatial distribution of pelagic longline core fishing fleets in 2018 (i.e., vessels assigned to a cluster for 2 or more years). To highlight focal fishing grounds and minimize overplotting, only those 0.25 grid cells where $\log(\text{fishing hours}) > 1.5$ are shown. RFMO boundaries are delineated by solid (WCPFC) and dashed (IATTC) black lines.

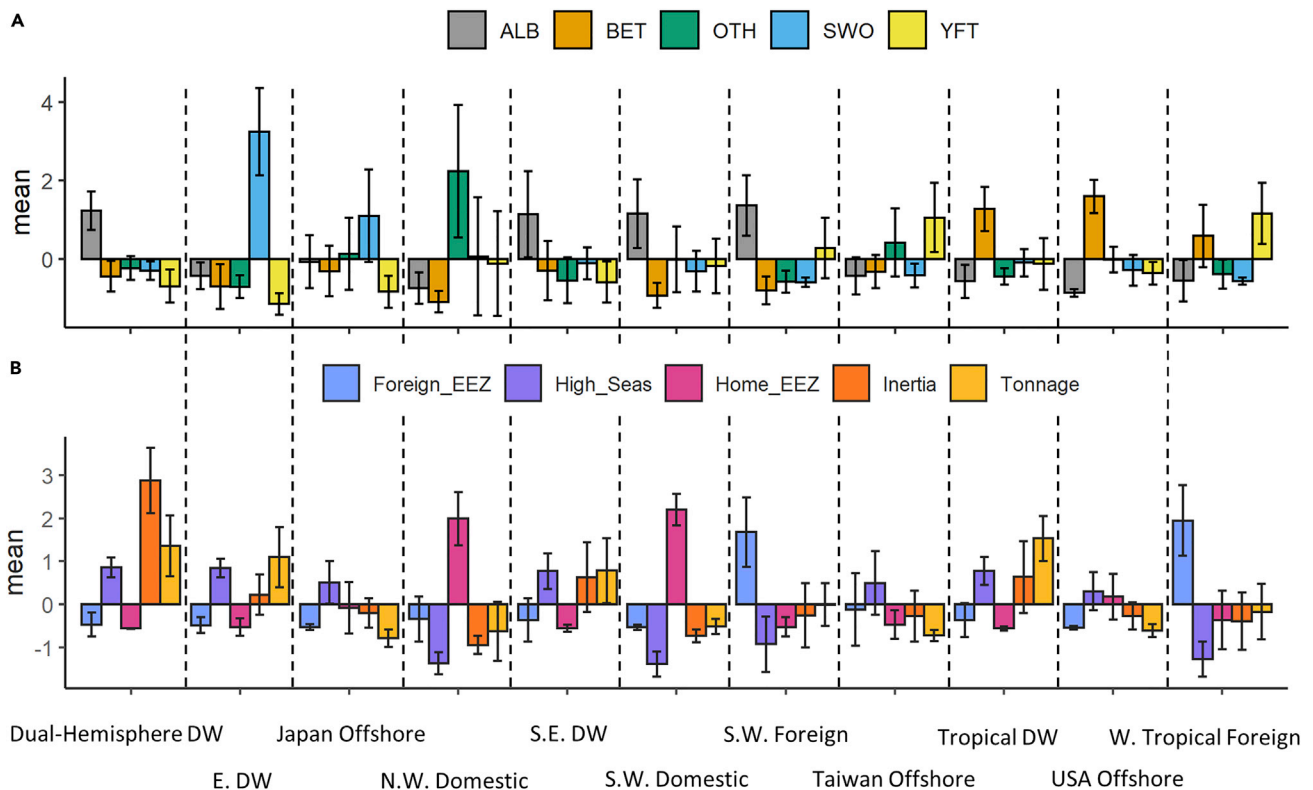


Figure 5. Distinguishing features of Pacific longline fishing fleets

Each panel depicts relative values of scaled dissimilarity layer inputs per core fishing fleet (i.e., mean \pm SD of all included vessels) across the study period. y axis values indicate the degree to which normalized inputs were positively or negatively associated with a particular cluster as compared with other clusters.

(A) Estimated vessel targets (% albacore [ALB], bigeye [BET], other [OTH], swordfish [SWO], and yellowfin [YFT]) contributing to the “Est. Overlap” dissimilarity layer.

(B) Combination of metrics contributing to the EEZ behavior (% Foreign EEZ, High-Seas, Home EEZ), characteristics (tonnage), and annual inertia (primary axis of dispersion) dissimilarity layers.

for all vessels, regardless of size or fishing location.⁸⁰ In contrast, China’s Pacific longline DW fishing operations have expanded rapidly in recent years as fueled by those purpose-built albacore tuna fishing vessels that dominate the Southwest Foreign and Southeast DW fishing fleets. This expansion is part of a national development plan designed to reduce pressure on coastal fisheries, provide work for shipyards, supply raw materials to domestic fish factories, and expand diplomatic influence.⁸¹ Although Korea, Japan, Taiwan, and China remain the dominant DW fishing nations, the number of vessels flagged to other states has increased as a number of operators have begun relying on open registries and/or flags of convenience to avoid those regulations whose enforcement is contingent on the engagement and goodwill of national authorities.^{82,83}

Confronted with declining economic returns, many DW fishing fleets across the Pacific have adopted new technologies and operational strategies to remain profitable. As advancements in freezing technology and increased fish hold capacity have improved product quality and extended the duration of fishing trips, transshipment and government subsidies are increasingly relied on to mitigate fuel expenditures.^{18,84} Concurrently, advancements in fishing technology (electronic navigational devices, synthetic hooks and lines, hydraulic winches, etc.) have

increased fishing power and improved search efficiency.^{6,85} Although many management measures have sought to limit fishing effort by capping the number of vessel days, the number of hooks deployed across Pacific fishing grounds has increased steadily over the past several decades (Figure S1) with new technologies facilitating the targeting of deep-dwelling species such as adult bigeye tuna.⁴³ Several recent studies have warned that human rights violations and deteriorating labor conditions are an emergent issue as some longline fishing operators seek new ways to offset fixed costs.^{18,51} Although we add our voice to those cautioning against broad-scale characterizations⁸⁶ given substantial operational heterogeneity within and across the sector, such reports warrant immediate attention and additional investigation. Encouragingly, a number of RFMOS, sub-regional governance bodies, and individual flag states have recently announced commitments to establish and enforce the labor standards designed to protect the rights of pelagic longline crew members.^{87,88}

Mismatches in the scope of monitoring and management

Our integrated analysis of regional catch and effort reports highlights a lack of uniformity in the collection of data and provision of

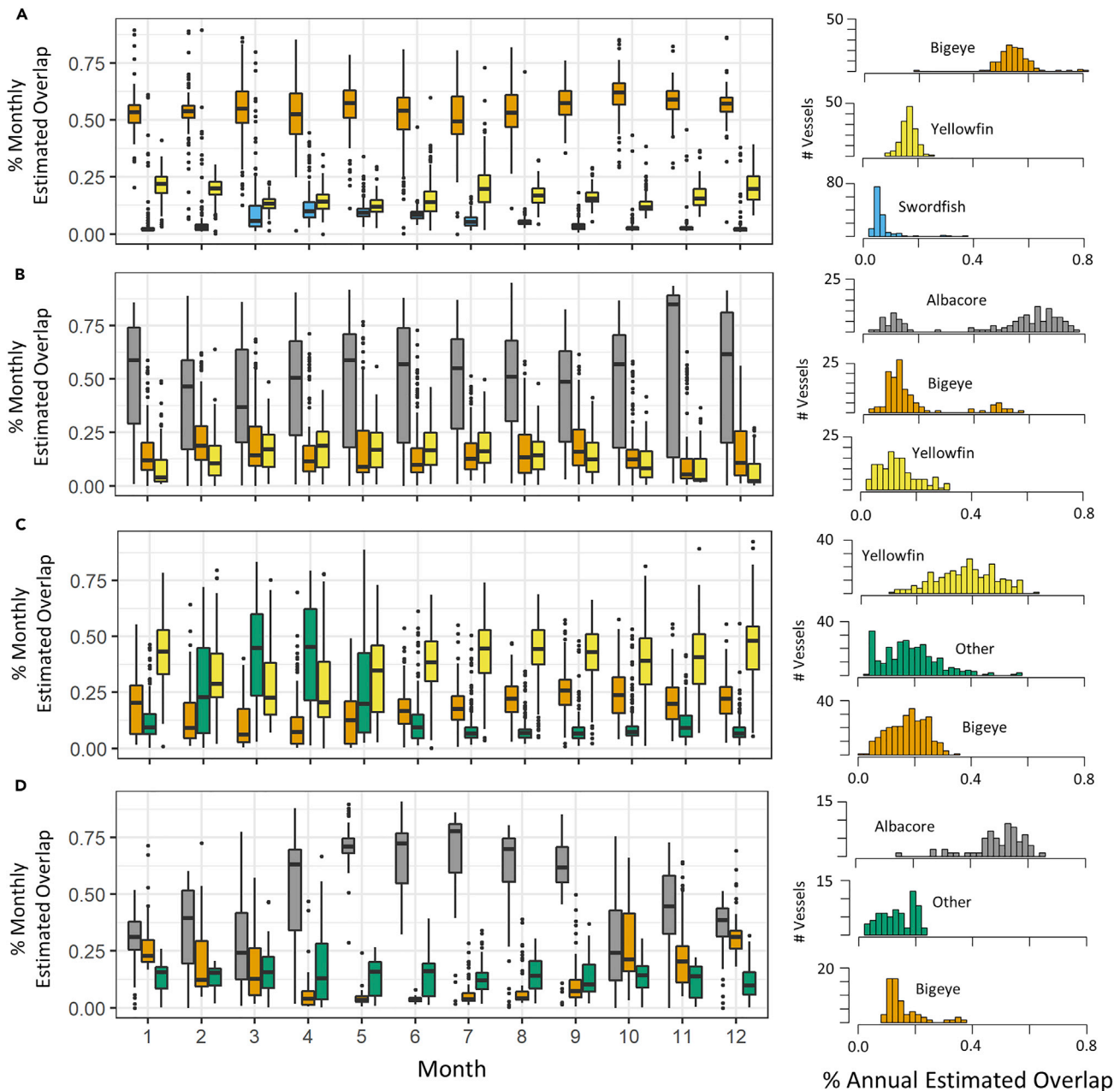


Figure 6. Seasonal overlap with gridded longline catch reports

(A–D) These panels contain boxplots depicting the distribution of monthly estimated overlap (%) of individual vessels comprising example fleets (left) in addition to histograms displaying the relative distributions (by species) of total annual estimated overlap of the same vessels. These comparisons are shown for the USA Offshore (A), Southeast DW (B), Taiwan Offshore (C), and Dual-Hemisphere DW (D) fleets.

public information across Pacific pelagic longline fisheries that may function to impede scientific research and sustainable management. Despite international standards and self-imposed mandates, considerable shortcomings exist in the resolution, completeness, and availability of fisheries data provided by RFMO member and non-member nations,^{25,89} as well as internal information regarding monitoring and compliance collated by the RFMOs themselves.⁹⁰ Although some nations and fishing fleets have consented to the release of high-resolution, spatiotemporal

fisheries data (i.e., operational data), others release only annual totals and/or restrict access to approved scientific commissions.⁹¹ In particular, some longline fisheries interacting with species of conservation concern (i.e., sharks and bluefin tuna) and some coastal/offshore fleets operating in the Northwest Pacific and Eastern Tropics and Subtropics are characterized by a lack of transparency because of unreliable or incomplete catch reports, limited observer coverage, and/or strict confidentiality requirements.^{17,92,93} Across the Pacific, those public domain

datasets that do exist are often inadequate for fundamental research applications because of a lack of metadata, limited fields or attributes, and low spatiotemporal resolution.^{25,90} With persistent uncertainty regarding the accuracy of vessel logbooks and the quantity of catch discarded or transshipped at sea, some researchers have questioned whether the data inputs used to determine harvest controls accurately reflect the activities of all fishing fleets and geographies.^{15,94,95} In fact, recent reports assert that unreported or misreported fishing rather than illegal, unlicensed activity may be the primary factor inhibiting the sustainable management of Pacific tuna fisheries.^{15,96,97} With longline data relied on as one of the few standardized abundance indices for regional stock assessments, addressing and resolving any such bias is of critical importance.

The sustainability of fisheries and other social-ecological systems depends in part on the fit between institutions, the problems they are meant to address, and the ecological and human contexts in which they operate.⁹⁸ To manage natural resources effectively, the governance system must fit, or align with, the characteristics of the biophysical system and the extractive activities it supports.⁹⁹ Within the context of pelagic longline fisheries, issues of fit arise not only in the standardization of data collection but also in the scale and scope of management. Despite evidence that inappropriate assumptions about the spatial structure of stocks and the behavior of fishing vessels can limit management effectiveness,^{100,101} the management of transboundary fisheries is often based on political realities and data availability rather than biological and/or operational considerations. Many species targeted or bycaught by pelagic longline fisheries are highly migratory, capable of traversing multiple management zones across the Pacific basin to reach foraging or breeding grounds.¹⁰² Although some stocks are managed across jurisdictional boundaries (e.g., Pacific bluefin tuna and North Pacific albacore), single-species, single-area measures continue to represent the default approach.

Our analysis highlights the activity of a number of multi-national, multi-specific fishing fleets targeting biogeographic regions that span multiple management areas (i.e., the US Offshore, the Dual-Hemisphere DW, the Tropical DW, and the Southeastern DW fishing fleets). Such connectivity emphasizes the need for increased coordination across RFMOs, sub-regional governance bodies, and individual assessment teams and suggests that effort controls and reporting and monitoring requirements may be better targeted as applied to fishing fleets with common strategies and tactics, rather than vessel flags or tonnage. In addition to efforts designed to identify and resolve the migration patterns, population structure and reproductive dynamics of transboundary target species,¹⁰³ effective ecosystem-based management will likely require synthetic efforts to (1) address the operational distributions of different fishing fleets and gear configurations, and (2) quantify their interactions with different species and life history stages over time and space.

Big ocean data and Pacific fisheries governance

With observer coverage across the pelagic longline sector limited by program costs, logistical constraints, and safety concerns,¹⁶ remote electronic monitoring tools like AIS and VMS are increasingly being used to satisfy international requirements for

independent data collection and exchange. Large quantities of low-cost data, as parsed by data mining and artificial intelligence algorithms, are helping to resolve operational uncertainties while providing scientists, managers, and seafood consumers with new information and insights.¹⁰⁴ In addition to satellite-based vessel-tracking systems, on-board video imagery and gear sensors are gaining popularity as reliable and unobtrusive means of quantifying target and non-target species interactions and monitoring compliance.^{16,105} In the near future, onshore agents may have the ability to audit in near real-time whether catch is accounted for, licensing conditions are complied with, and appropriate revenue is collected.¹⁵

Although new digital technologies have reduced the cost of collecting, processing, and transmitting fisheries data, on their own they are unlikely to address the enduring sustainability concerns and governance challenges associated with pelagic longline fisheries.^{11,106} Data provide a helpful view of the world, but only to those with the ability to access it and the ability to interpret and use it.^{107,108} With many governance bodies often already limited by funding, data processing, and analytical capacity,⁹⁶ a continued adherence to confidentiality requirements may limit the production and transfer of knowledge. Future efforts designed to delineate, describe, and assess behavior across the pelagic longline sector would benefit from the revision of data-sharing agreements to increase the accessibility of $1 \times 1^\circ$ gridded catch and effort data (already available for purse seine and pole-and-line fishing fleets) and vessel-level data (i.e., VMS records, electronic monitoring and observer reports, and transshipment logs) to individuals not formally employed or contracted by RFMOs. Globally, fisheries data analyst roles and responsibilities are increasingly being transferred from public organizations reliant on private data to private actors capable of leveraging public data to accelerate research and development.²³ Yet, this devolution of fisheries monitoring and enforcement to non-state actors may entail risks and opportunities that are not yet fully understood.¹⁰⁴ Although the emergence of the digital ocean ecosystem has led to unquestionable scientific advances, it has also raised concerns regarding the equity of data-processing algorithms, the control of information flows, and the determination of research priorities.^{23,109–111} With big ocean data restructuring the relationships between scientists, policymakers, and fisheries stakeholders, the resulting reconfiguration of power may be irreducible to whose interests are served.^{112,113}

Moving forward, policymakers and governments should identify strategies to diversify who benefits from the digital ocean ecosystem, empowering fishers and non-state groups such as RFMOs that may be unable to finance cutting-edge technology.¹⁰⁸ For environmental NGOs, the pursuit of high-profile initiatives capable of garnering public interest and philanthropic support should be balanced with the more mundane, but potentially transformative activities required to improve record-keeping, build digital infrastructure, and democratize data availability.¹¹⁰ Critically, stated commitments to transparency and reproducibility should be honored in the pursuit of licensing agreements that ensure public access underlying data sources in addition to summarized outputs. Provision of gridded VMS data and vessel tracks produced by both AIS data and VMS data prior to aggregation would improve subsequent fleet clustering efforts and facilitate the type of comprehensive and

high-resolution analyses required to distinguish between different patterns of gear usage (i.e., shallow versus deep-set longlines) and identify behavioral anomalies linked with human rights concerns and unsustainable and/or unauthorized fishing practices. Likewise, individual nation states and RFMOs may have a role to play by using common formats, improving data access, and decentralizing analysis. Across sectors and scales, more active and meaningful engagement with seafood producers and processors is needed to help align incentives, build trust, and address the privacy concerns that have long constrained the provision of public data within these common pool resource systems. Remote electronic monitoring may in fact provide new economic opportunities for fishers willing to engage with the digital ocean ecosystem. Lower tracking and verification costs could reduce information asymmetries across seafood supply chains and allow producers the opportunity to better differentiate their activities and products in pursuit of the market premiums increasingly associated with sustainability and traceability.¹⁰⁴ Although such reforms may present logistical, procedural, and legislative challenges, the sustainable and equitable management of transboundary fisheries in the 21st century may be contingent on embracing innovation to improve transparency and accountability.^{107,114}

Management and policy recommendations

Functional fishing fleets represent a promising management unit for complex, multiscalar tuna fisheries across the Pacific Ocean, as well as marine social-ecological systems more broadly. Organizing fishing effort by vessel behaviors and attributes may help to standardize existing area-based fleet designations, while refining the accuracy of the catch, effort, and selectivity parameters they are meant to describe. The “areas-as-fleets” approach currently used by many stock assessments (in which selectivity and catchability vary by fixed, rectangular boxes) endeavors to capture fishing fleet heterogeneity by employing stratification systems based on variable combinations of country, gear, set type, area, catch unit, and season variables. Yet, the large number of resulting designations may be of coarse spatial and temporal scale and/or uneven distribution. For example, out of the 27 longline fishing fleets identified in the most recent stock assessment as interacting with North Pacific albacore, there are 19 Japanese units as compared with only 2 from Taiwan.¹¹⁵ Yet our analyses (Figure 4) and other observations⁶ have noted that vessels from both nations increasingly operate as mixed-flag fleets that transverse the area boundaries used for such designations in relevant portions of the Kuroshio Current system (e.g., the Taiwan Offshore and Japan Offshore fleets; Figure 4).

In an increasingly globalized economy where DW fishing has become more common¹⁸ and corporate ownership of fishing vessels frequently transcends national borders and jurisdictions,^{19,116} fleet designations based on flag state and gear type alone likely fail to capture the operational distinctions driving at-sea variation in behavior and decision-making.¹¹³ Although much of the current discourse surrounding high seas fisheries focuses on the identification of nations responsible for IUU fishing, in the short-term such characterizations may function to (1) obscure the transnational seafood actors and supply chains driving such behaviors^{116,117} and (2) dissuade national fisheries

organizations and agencies from sharing data and participating in collaborative management processes. Where previous work has documented regional patterns of observed²⁹ and unauthorized high seas transshipment activity,¹¹⁸ port usage,³¹ and vessel ownership¹⁹ by flag state, in the future functional fishing fleets identified on the basis of such metrics could be used to identify the specific actors, markets, and supply chains associated with such activities and, where called for, aid in the design of the targeted interventions needed to disrupt them.

Conclusions and future directions

This characterization of the activity patterns of pelagic longline fishing fleets in the Pacific is just the beginning of a more nuanced understanding of the sector. Undoubtedly, as data quantity, quality, and availability increase, additional fleets with unique behaviors and attributes will emerge from those we have described. Nevertheless, our results provide valuable evidence of the utility of disaggregated fisheries analyses that integrate descriptive vessel information and tracking data with catch reports to identify and describe the behaviors and attributes of distinct fishing fleets. In the future, such classified groups have great potential to serve as a foundation for a more differentiated and targeted approach to fisheries research, monitoring, and management.¹¹⁹ Across other disciplines, the utility of disaggregated units is already recognized as critical for the monitoring and management of human-environment interactions.^{120,121} For transboundary fisheries in the Pacific Ocean, fleet-disaggregated analyses could be used to (1) address the differential effects of time/area closures and catch quotas, (2) analyze the competition for space among sectors (i.e., large-scale versus small-scale, longline versus purse-seine) and emerging ocean users (i.e., offshore wind farms, aquaculture operations, and deep-sea mining claims), (3) study the socioeconomic attributes and/or environmental associations of different fishing livelihood strategies, (4) estimate bycatch and non-target species interactions, and (5) audit self-reported logbook records. Given the degree to which concerns regarding the relative distribution of costs and benefits continue to impede the adoption of pelagic longline management and conservations measures⁷⁷ and recent research regarding the asymmetrical impacts of climate change on regional fishery landings and revenue,⁹ we suggest such applications are particularly salient for transboundary fisheries across the Pacific.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests should be directed to and will be fulfilled by the lead contact, Timothy H. Frawley (tim.frawley@noaa.gov).

Materials availability

The final list of cluster assignments for all pelagic longline fishing vessels observed in the study area between 2017 and 2019, can be accessed at Zenodo: <https://doi.org/10.5281/zenodo.6968472>.

Data and code availability

All vessel registration, vessel tracking, and fisheries-dependent catch and effort data used in this study are public and available online or on request. WCPFC longline annual yearbook totals were downloaded from <https://www.wcpfc.int/statistical-bulletins>, WCPFC longline gridded catch and effort data were downloaded from <https://www.wcpfc.int/folder/public-domain-data>, and WCPFC registry information was downloaded from <https://www.wcpfc.int/doc/historical-record-fishing-vessels-rfv-data/>. IATTC longline

annual yearbook totals and gridded catch and effort data were downloaded from <https://www.iattc.org/en-US/Data/Public-domain>, while IATTC registry data were made available on written request to IATTC staff. AIS-based Fishing Effort and vessel registration and gear usage data were downloaded from <https://globalfishingwatch.org/data-download/datasets/public-fishing-effort>. Instructions and original code used to process and analyze public data hosted by other organizations can be accessed from a GitHub repository (https://github.com/thfrawley/OneEarth_Pelagic_LongLine) archived through Zenodo: <https://doi.org/10.5281/zenodo.6968472>. The Maritime Boundaries shapefile in this repository from which EEZ usage calculations are derived was modified from a version available at <https://www.marinerregions.org/downloads.php>.

RFMO data processing

Pacific longline catch and effort data were obtained from public domain records available for download on websites hosted by the IATTC (version dated 9/11/2020) and the WCPFC (version dated 3/25/21). The IATTC data used for analysis were grouped by year, flag, month, and $5 \times 5^\circ$ grid cell. Prior to integration with WCPFC data, gridded IATTC data were processed to convert catches reported only in numbers to weight (~29.8% of tuna and billfish records and ~62.5% of shark records from 2017 to 2019). Cell- and species-specific conversion factors were generated by calculating the average weight/number ratio of all flag-state records where both weight and number were reported concurrently throughout the complete dataset (1978–2019) after outliers (those values outside the 98% quantile distribution) were excluded. In the absence of any concurrent records for a given species in a given cell, conversion factors were assigned using inverse distance weighted interpolation in the R package “gstat.”¹²² Following the calculation of missing weights, IATTC catch and effort data were aggregated across flag states. The WCPFC data used for analysis were grouped by year, month, and $5 \times 5^\circ$ grid cell, with the vast majority of catch records from 2017–2019 (~96.5%) reported in both number and weight. Prior to integration with IATTC data, WCPFC data associated with cells between 150° W and 130° W and 50° S and 4° S were removed to prevent the duplication of records associated with a region of overlapping jurisdiction in the Eastern Pacific. Recent and historical RFMO vessel registries used to contextualize AIS observations (i.e., Figure 2) were accessed online (WCPFC, 2019 data pulled from historical registry, version dated 3/9/2022) or on request from RFMO staff (IATTC, 2019 data pulled from recent registry, version dated 8/5/2020) with dual registration inferred on the basis of repeated registration numbers, International Maritime Organization (IMO) ship identification numbers, and/or International Radio Call Sign (IRCS) identifiers.

AIS data processing

AIS fishing effort and vessel data (Version 2.0; updated 3/18/2021) were obtained from Global Fishing Watch (GFW)-maintained public databases available for download on their website. The determination of whether a vessel was engaged in fishing activity and the type of fishing gear utilized were specified using the methodology described by Kroodsma et al.²⁶ For our analyses, we used the subset of vessels using pelagic (i.e., “drifting”) longline fishing gear and cropped the global data to retain only those records within the combined spatial extent of the IATTC and WCPFC convention areas. Although fishing activity and gear type detection algorithms are known to be imperfect,¹²³ potentially leading to the misclassification of some vessels and activities, they have been shown to characterize longline fishing activity with a high degree of accuracy (precision = 0.88, recall = 0.94, F1 score = 0.91) as compared with other gear types.²⁸ Raw daily data were downloaded, processed, and clustered at 0.1° resolution but were subsequently aggregated to 0.25° prior to plotting in order to facilitate basin-scale data visualization. We chose to include only data from 2017 to 2019 in the final analysis because this was the temporal extent of maximum AIS usage and satellite coverage (both of which have progressively increased over the last decade) for which we also had access to RFMO catch and effort data.

Clustering metrics

Six clustering metrics were calculated annually for each vessel active that year. Vessel characteristics (i.e., length and tonnage) were obtained from a vessel characterization algorithm developed by GFW²⁶ as accessed through data available on their website. To assess differences in the geographic location of fishing activity, we used seasonal COG (i.e., the weighted, geographic centroids

of seasonal fishing effort).^{124,125} COG was assessed independently for both summer (April–September) and winter months (October–March) to reflect the seasonality of fishing grounds^{26,126} with resulting latitude and longitude measurements subsequently converted to Cartesian coordinates (x,y,z) in order to reflect distances associated with the curvature of the earth. To distinguish between those vessels targeting localized areas and those vessels whose effort was distributed more broadly, we calculated vessel inertia (i.e., the geographic range of fishing effort, calculated as the mean square distance between fish cells and the annual centroid of fishing effort).^{45,127} Inertia calculations yielded the length (km) of the two dominant axes of dispersion, collectively considered as a measurement of the total space occupied (i.e., the fishing footprint) of observed vessels.¹²⁵ EEZ behavior was calculated as the number of hours each year that each vessel spent fishing territorial or sovereign waters of that vessel’s flag state, territorial or sovereign waters of other nations, and the high seas and subsequently dividing each of these values by the total number of fishing hours to obtain a percentage. This metric was intended to identify fleets operating on the high seas in areas beyond national jurisdiction in addition to distinguishing those vessels operating in domestic waters from those licensed through joint-venture fishing agreements (joint-venture vessels relinquish the right to fish the high seas in exchange for permission to enter foreign EEZs). Maritime boundaries were obtained from a shapefile (Version 11; updated 11/18/2019) available online for download (see data code and availability), and the R package “sf”¹²⁸ was used for related geospatial data calculations.

Estimated species targeting was inferred using gridded, basin-scale RFMO data aggregated across flag states (see above). The relative contribution (% weight) of individual species to the total catch reported in each cell across the Pacific Basin during each month of our study period ($n = 36$) was first calculated by dividing the catch weights associated with albacore tuna, bigeye tuna, yellowfin tuna, swordfish (i.e., the four dominant species by weight in the combined dataset), and other species (skipjack tuna, striped marlin, blue marlin, black marlin, sharks, and unidentified species as aggregated into a single category) by the total reported catch weight. Note that although Bluefin tuna is a traditionally important target for many pelagic longline fisheries, it is not identified by name in publicly available datasets. Next, AIS fishing effort data were aggregated for each vessel to match the spatial and temporal resolution of RFMO data (i.e., by year, month, and $5 \times 5^\circ$ grid cell). We estimated the % effort allocated to each of our five species categories by each vessel each month by weighting the percentages reported in each 5×5 cell where that vessel was observed fishing by the relative amount of time a vessel spent fishing in that cell as compared with other cells (i.e., a vessel spending three-fourths of its fishing time in one cell and one-fourth of its time in another cell would have the percentages reported in the first cell contribute $3 \times$ the amount to its monthly estimated targets as the percentages reported in the second cell). Annual estimated target species for each vessel were inferred by weighting monthly estimated targets for each month in which a vessel was active equally.

Clustering procedure

A vessel dissimilarity matrix describing the pairwise distinction between vessels was calculated for each metric and each year using normalized Euclidean distances within the R package “distances.”¹²⁹ In cases where vessel data were missing (i.e., a vessel was inactive during the winter months), the mean vessel dissimilarity of all vessel pairs for that metric that year was assigned to the matrix cells (i.e., pairwise comparisons) associated with that vessel. The six dissimilarity matrices (i.e., Summer COG dissimilarity, Winter COG dissimilarity, Inertia dissimilarity, EEZ Behavior dissimilarity, Estimated Targeting dissimilarity, and Vessel Characteristics dissimilarity) were then averaged to calculate the average annual vessel dissimilarity matrix used as the input for clustering (Figure 3A). The advantages of using a single, average dissimilarity matrix as an input for clustering rather than a complete and untransformed data frame of observations (rows) and variables (columns) were that (1) our approach ensured that all metrics would be weighted equally regardless of the number of component variables, and (2) imputing mean dissimilarity for vessels with missing data rather than the mean of an untransformed variable ensured that two vessels with missing data were not assessed and compared on the basis of identical imputed attributes for that variable.

Following the calculation of each average annual vessel dissimilarity matrix, the Partitioning Around Medoids (PAM) clustering algorithm was used,¹³⁰ implemented in the R package “cluster.”¹³¹ Compared with the typical k-means

clustering approach, PAM is considered more robust and less sensitive to outliers because it minimizes a sum of dissimilarities instead of a sum of squared Euclidean distances. The PAM algorithm requires the number of clusters to be generated to be specified *a priori* by the user. In order to estimate the optimal number of clusters (k), we used the average silhouette method, which measures the quality of clusters over a range of possible values for k , with higher average silhouette width indicating better clustering.¹³⁰ Because k varied across the 3 years of our study period because of differences in AIS coverage (1,777 vessels in 2017, 1,939 vessels in 2018, and 2,085 vessels in 2019) and vessel behavior (i.e., interannual variation in the location of pelagic fishery hotspots), the final value selected (i.e., $k = 11$) was based on the highest average k value (Figure 3B). Annual clusters were visualized using multi-dimensional scaling plots where differences between vessels assessed in the average annual dissimilarity matrix were reduced to two dimensions (Figure 3C) using principal coordinates analysis.¹³² Within (intra-) and between (inter-) cluster relationships were validated and quantified using (1) complete intracluster diameter (the distance between the two most remote objects belonging to the same cluster), (2) average intracluster diameter (the average distance between all samples belonging to the same cluster), and (3) average intercluster linkage (the average distance between all samples belonging to two different clusters implemented in the R package “clv”).¹³³

Cluster naming and fleet assignment

Individual, annual clusters were named using conventions based on the nationality, size, and behavior of member vessels. Clusters where >66% of member vessels were from the same nation were assigned that name as lead descriptor. Clusters consisting of vessels of mixed nationality were assigned a lead descriptor based on the geographic location of focal fishing grounds. Clusters consisting of vessels principally operating in the EEZs of their flagged nations were assigned “domestic” as a second descriptor, while clusters consisting of vessels principally operating in EEZs of other nations were labeled “foreign.” This naming convention follows previously established conventions.^{6,12} Clusters of smaller vessels (<100 GRTs) operating in the high seas were labeled as “offshore,” while clusters of larger vessels (>100 GRTs) were labeled as “DW.” A number of vessels active multiple years were associated with multiple clusters. In addition to being impacted by differences in AIS coverage (see above), changes in cluster association were likely driven by interannual variation in (1) pelagic fishery hotspots and (2) individual decision-making in the selection of fishing grounds and target species. In order to highlight core characteristics and attributes of identified fishing fleets, we subsequently applied a filter to retain only those vessels associated with the corresponding cluster for 2 or more years (i.e., Figures 4C, 5, 6, and S3). To maximize included data, the “East Tropical DW” cluster that appeared only in 2017 was grouped with the “Tropical DW” cluster when applying this rule as justified by the high degree of connectivity and overlap between the vessels comprising these two groups during the initial clustering process (Figure 4B). A relative comparison of cluster inputs (Figure 5B) characterizing our core fishing fleets (i.e., vessels assigned to the same cluster for 2 or more years) was conducted by normalizing the cluster inputs (enabling comparisons across scales) for fleet-associated vessels across the 3 years of our study and then calculating the mean and standard deviation of all normalized values associated with each fleet.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.oneear.2022.08.006>.

ACKNOWLEDGMENTS

This work was supported by a grant from the National Oceanic and Atmospheric Administration Fisheries Office of Law Enforcement (NOAA OLE; NA20OAR4320278). We would like to thank NOAA OLE staff, members of the United States Coast Guard, the Pacific Fishery Management Council’s Highly Migratory Species Advisory Subpanel, and GFW for helping to direct the research with their ideas, opinions, and experiences; Valerie Post (WCPCFC), Nick Vogel (IATTC), and Peter Williams (SPC) for helping to facilitate access to vessel registries and public gridded catch and effort data; and Jon Lopez, Carolina Minte-Vera, Steven Teo, Keisuke Satoh, Masanori Miyahara,

Sheng-Ping Wang, Angela Abolhassani, and Kamal Azmi for comments and discussion on earlier drafts of the manuscript.

AUTHOR CONTRIBUTIONS

Conceptualization, T.H.F., B.M., E.L.H., M.G.J., and S.B.; funding acquisition, T.H.F., B.M., and M.G.J.; methodology, T.H.F., B.M., and H.W.; investigation, T.H.F.; visualization, T.H.F., H.W., and S.B.; validation, S.-K.C., M.J., F.B., and Q.H.; writing – original draft, T.H.F., H.W., S.B., K.L.S., and B.M.; writing – review & editing, T.H.F., K.L.S., S.-K.C., M.J., F.B., E.L.H., M.G.J., and S.B.; supervision, M.G.J., E.L.H., Q.H., and S.B.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: January 20, 2022

Revised: June 17, 2022

Accepted: August 18, 2022

Published: September 16, 2022

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