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Distant-water industrial fishing in high diversity regions

Sam McClatchie[1]

[1]FishOcean Enterprises

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Abstract

High diversity of coastal fishes is found in Western Pacific, East Asian, Australasian, Southern African and Caribbean waters, while the greatest diversity of tunas and bill-fishes is found in Tasman Sea, Equatorial Pacific and Southern African waters. I used publicly available Global Fishing Watch data to map industrial fishing activity during 2018 in six broadly defined High Diversity Regions (HDRs): Western Pacific, Eastern Pacific, Southern Africa, Australasia, Tasman Sea and Central America. Automatic Identification System (AIS) metadata for vessels identified as fishing by Global Fishing Watch were used to partition fishing hours by vessel class and flag state. Drifting long-lines, tuna purse seines, squid jigging and trawling dominated AIS-inferred effort (vessel power X fishing hours) in different HDRs. Large numbers of fishing vessels are operating in High Diversity Regions. Based on AIS reporting, a minimum total of 2,276 registered drift longliners, 475 tuna purse seiners, 693 trawlers, and 340 squid jiggers were fishing in the six HDRs during 2018. The top three flagged countries account for 56 - 75% of drift longline activity, 89 - 99% of trawling, and 99% of squid jigging. There is a wide range of flagged countries fishing purse seines, with the top three accounting for only 33 - 56% of activity in the HDRs. East Asian fleets account for 99% of squid jigging, and 25 - 75% of drift longlining, but only 0 - 31% of purse seine and 0 - 12% of trawl fishing in High Diversity Regions. The Western Pacific and Southern African HDRs are subject to more fishing activity than other HDRs, and the most common fishing gear used is drift longlining. China and Taiwan have the largest number of registered drift longline vessels in these regions. Longline and purse seiner fleets had surrounded large Marine Protected Areas by 2018, indicating both successful exclusion, and the potential for encroachment of protected areas by industrial fleets. Real-time monitoring guiding targeted enforcement provides hope for protecting the High Diversity Regions of the world ocean from distant water fleets, which admittedly is only one of the threats that they face in a changing climate.

Distant-water industrial fishing in high diversity regions

Sam McClatchie

FishOcean Enterprises, 38 Upland Rd, Huia, Auckland 0604, New Zealand

Abstract

High diversity of coastal fishes is found in Western Pacific, East Asian, Australasian, Southern African and Caribbean waters, while the greatest diversity of tunas and billfishes is found in Tasman Sea, Equatorial Pacific and Southern African waters. I used publicly available Global Fishing Watch data to map industrial fishing activity during 2018 in six broadly defined High Diversity Regions (HDRs): Western Pacific, Eastern Pacific, Southern Africa, Australasia, Tasman Sea and Central America. Automatic Identification System (AIS) metadata for vessels identified as fishing by Global Fishing Watch were used to partition fishing hours by vessel class and flag state. Drifting longlines, tuna purse seines, squid jigging and trawling dominated AIS-inferred effort (vessel power X fishing hours) in different HDRs. Large numbers of fishing vessels are operating in High Diversity Regions. Based on AIS reporting, a minimum total of 2,276 registered drift longliners, 475 tuna purse seiners, 693 trawlers, and 340 squid jiggers were fishing in the six HDRs during 2018. The top three flagged countries account for $56 - 75\%$ of drift longline activity, $89 - 99\%$ of trawling, and 99% of squid jigging. There is a wide range of flagged countries fishing purse seines, with the top three accounting for only $33 - 56\%$ of activity in the HDRs. East Asian fleets account for 99% of squid jigging, and $25 - 75\%$ of drift longlining, but only $0 - 31\%$ of purse seine and $0 - 12\%$ of trawl fishing in High Diversity Regions. The Western Pacific and Southern African HDRs are subject to more fishing activity than other HDRs, and the most common fishing gear used is drift longlining. China and Taiwan have the largest number of registered drift longline vessels in these regions. Longline and purse seiner fleets had surrounded large Marine Protected Areas by 2018, indicating both successful exclusion, and the potential for encroachment of protected areas by industrial fleets. Real-time monitoring guiding targeted enforcement provides hope for protecting the High Diversity Regions of the world ocean from distant water fleets, which admittedly is only one of the threats that they face in a changing climate.

Keywords: commercial fishing, species diversity, fishing effort, fishing gear, flag state, Marine Protected Areas

Email address: smcclatchie@fishocean.info (Sam McClatchie)

1. Introduction

Biodiversity can be defined in many ways (Magurran, 2013), but the most common method is an approximate measure of the number of species in an area, commonly referred to as species richness. High Diversity Regions (HDRs) are characterised by unusually high species richness. Recent studies of marine biodiversity have identified regions with higher than average diversity (Tittensor et al., 2010), including biodiversity hotspots (Price, 2002). Many of these High Diversity Regions are also targeted by industrial fisheries (Watson and Tidd, 2018), on the high seas with limited fisheries management, usually with insufficient monitoring and enforcement of protected zones. Monitoring of fishing effort on the high seas is conducted by Regional Fisheries Management Organizations, and the data can be both scattered and incomplete, despite recent attempts to consolidate, merge and analyse them (Anticamara et al., 2011; Bell et al., 2017; Coulter et al., 2020; Watson, 2017). Recent establishment of large Marine Protected Areas (MPAs)($>= 100,000\ km^2$) in High Diversity Regions raises the spectre that they could become "paper parks" unless the MPAs are adequately monitored and their protection enforced. Further, it is currently not well known how heavily exploited are areas outside the established MPAs, but still within High Diversity Regions.

The boundaries of marine HDRs are broadly known, but poorly defined. An additional complication is that different species groups, such as coastal fishes, tunas and billfishes, or squids are most diverse in different regions. The highest diversity of coastal fishes is found in Western Pacific, East Asian, Australasian, Southern African and Caribbean waters (Tittensor et al., 2010). In contrast, greatest diversity of tunas and billfishes is found in the Tasman Sea, Equatorial Pacific and Southern African waters (Tittensor et al., 2010). Squids show highest diversity off the U.S. Atlantic seaboard, Northwest Africa and off Japan (Tittensor et al., 2010). For this paper I focused on high diversity areas for coastal fishes, tunas and billfishes. Because the boundaries are not well-defined, I chose relatively large areas for each region to include as much of the regional high diversity areas as possible.

We used the Global Fishing Watch (GFW) program dataset (Kroodsma et al., 2018) to map the spatial distribution of industrial fishing in six HDRs (Western Pacific, Australasia, Southern Africa, Eastern Pacific, Tasman Sea and Central America). In addition I ask several specific questions. Are some HDRs targeted more heavily than others? Are any particular nations or fishing gear type primarily responsible for the greatest AIS-inferred effort in the HDRs? Finally, what is the spatial distribution of fishing hours by flag state and fishing gear type in HDRs? While the fishing effort data that I analysed are limited to vessels reporting Automated Identification System (AIS) data, management implications can be drawn from this first order analysis, helping to better define regions where fishing effort should be managed. GFW AIS data are affected by progressive increases in the numbers of vessels reporting AIS signals, as well as by increasing numbers of satellites (Taconet et al., 2019). To reduce this potential source of bias I restricted my analysis to a single year (2018). More recent data have recently been publicly released, but were not available at the time of my analysis.

2. Materials & Methods

Daily Global Fishing Watch data at 1/10th degree grid resolution for 2018, and vessel identity data, were downloaded from `https://globalfishingwatch.org/data-download/datasets/public-fishing-effort` (last accessed 11 May, 2021). Daily files provided by Global Fishing Watch contain a global data set of times spent by vessels at each grid location derived from Automated Identification System (AIS) reporting as well as a unique vessel identifier (MMSI) associated with each reported position (de Souza et al., 2016). Times at location are a subset of vessel positions that have been designated as time when vessels are fishing determined using the Global Fishing Watch neural network model (Kroodsma et al., 2018). In this paper I refer to fishing times at location as fishing hours, and I calculated AIS-inferred effort as vessel engine power in kW X fishing hours/24 (kilowatt days).

Daily ascii files were converted to annual files using a Linux shell script to remove file header lines and sequentially concatenate the daily files. The annual files were converted to netcdf format and subset within polygons using the NCAR Command Language (`http://dx.doi.org/10.5065/D6WD3XH5`) to retain effort data for selected areas of the oceans known to have high marine biodiversity. The regionally subset effort files were merged with vessel identity data along common MMSI using the R Statistical Language (Ihaka and Gentleman, 1996). The merges created a new set of regional effort data based on hours at location during fishing (fishing hours) with associated vessel characteristics including flag state, vessel class, vessel length, tonnage, and engine power.

The number of unique vessels detected from AIS MMSI numbers was calculated for each region in each year. The spatial distribution and magnitude of AIS-inferred effort expressed as fishing hours at location were plotted for each region. Much more numerous lower effort data were separated from higher effort data to prevent the higher values being obscured. In addition, time series of AIS-inferred effort expressed as kilowatt days (vessel engine power in kW X fishing hours/24) were plotted for each region, separating each time series by vessel flag state and fishing gear type.

Fishing effort cannot be directly compared across gear types because different types of fishing are not comparable in the time to land fish. For example, drifting longlines may have a soak time of several days, while the detected fishing time for purse seines is much shorter, and includes time to empty the net. Bearing that in mind, I plotted the seasonal time series in each High Diversity Region for each of the three most common gear types ranked by cumulative effort during 2018. I restrict my comparisons to the same gear types across different regions.

3. Results

3.1. Spatial distribution of fishing fleets

Drift longline fleets fish more extensively in the High Diversity Regions (HDRs) than tuna purse seine, trawl, or squid jigging fleets (Figures 1-6). The drift longline fleets are so wide ranging that their fishing activities outline the MPAs and Exclusive Economic Zones (EEZs) that exclude them in the Tasman Sea (Figure 1b), Australasian (Figure 2b), Western Pacific (Figure 3b), and Southern African HDRs (Figure 4b). Tuna purse seine fleets also fish wide areas in parts of the the Australasian (Figure 2a) and Western

Pacific (Figure 3a) HDRs, where they are the second most spatially extensive fishing gear.

The Western Pacific HDR experiences greater longline AIS-inferred effort than other High Diversity Regions. Drift longline effort (median effort $161,046\ kWday^{-1}$) in the Western Pacific HDR was more than twice that in the Southern African (median $73,891\ kWday^{-1}$) and more than five times that in the Eastern Pacific HDRs (median $33,195\ kWday^{-1}$, Figure 7). Longline effort was also more seasonally continuous in the Western Pacific HDR compared to other regions. In contrast, longline fishing declined during austral summer in the Tasman Sea and Australasian HDRs, which differs from the Eastern Pacific where longlining effort was higher in the austral summer and declined during the austral winter (Figure 7).

Tuna purse seining effort was also higher in the Western Pacific than in the Eastern Pacific, Australasian and Central American HDRs (Figure 7). Tuna purse seine effort (median $42,761\ kWday^{-1}$) in the Western Pacific was approximately five times greater than in the Eastern Pacific (median $8,447\ kWday^{-1}$) and Australasian HDRs (median $9,059\ kWday^{-1}$), and almost fifteen times greater than in the Central American HDR (median $2,925\ kWday^{-1}$) (Figure 7).

3.2. Size and flag state of fishing fleets

Large numbers of fishing vessels are operating in the High Diversity Regions. Our estimates are conservative because they only include vessels reporting AIS signals. A total of 2,276 registered drift longliners, 475 tuna purse seiners, 693 trawlers, and 340 squid jiggers were fishing in the six HDRs during 2018. There are distinct regional differences in both the most common types of fishing and in the countries fishing the HDRs. The Western Pacific and Southern African HDRs are most heavily targeted by drifting longliners. 866 drift longliners (38% of all vessels of this class) were fishing in the Western Pacific HDR, and 536 (24%) longliners fished in the Southern African HDR, with 336 (15%), 315 (14%) and 223 (10%) drift longliners fishing the Australasian, Eastern Pacific, Tasman Sea HDRs, respectively. Tuna purse seiners were most active in the Western Pacific (237 vessels, 50% of vessels in this class) and Australasia (156 vessels, 33%). Large numbers of trawlers fished the Central American (430 trawlers, 62% of vessels in this class), Southern African (170 vessels, 25%), and Tasman Sea HDRs (93 vessels, 13%). 340 squid jiggers (100% of all vessels of this class) fished the Eastern Pacific HDR.

Fifteen to 41 flag states were fishing the High Diversity Regions in 2018. Seventy five percent of drifting longliners in the Western Pacific HDR and 63% of longliners in the Southern African HDR were flagged to China, Taiwan, Korea, and Japan. Compared to drifting longliners, tuna purse seiners were flagged to a wider range of countries in both the Western Pacific and Australasia, with a much smaller proportion of fishing conducted by Asian fleets (11% in the Western Pacific HDR and 31% in the Australasian HDR). U.S. vessels dominated trawling (97% of trawlers) in the Central American HDR, which includes the Gulf of Mexico. In the Southern African HDR, South African and Namibian trawlers were most common (61%). Squid jigging in the Eastern Pacific HDR was conducted almost entirely by Chinese vessels (97%). These data indicate that Asian fleets dominate drift longlining effort in the Western Pacific and Southern African HDRs, as well as squid jigging effort in the Eastern Pacific HDR. Tuna purse seining is conducted by a wide range of nations in the Australasian HDR, while trawling is dominated by U.S.

vessels in the Central American HDR (mainly in the U.S. EEZ) and by African countries in the Southern African HDR.

I examined the flag states of industrial fishing in each HDR by ranking flags by numbers of vessels for the two most common gear categories in each HDR. Table 2 shows the top three rankings for both gear categories in each HDR, where industrial fishing activity involving more than 100 vessels is highlighted. The highest numbers of industrial vessels fishing in the HDRs in 2018 were flagged to the United States, China, and Taiwan (Table 2). A large number (421 vessels) of U.S. flagged trawlers worked the Central American HDR in 2018 (Table 2 & Figure 6b). Most of these trawlers fished the northern Gulf of Mexico and the southwestern area off Florida (Figure 6b). Chinese flagged squid jiggers (331 vessels) and drift longliners (104 vessels) worked the Eastern Pacific HDR, which includes areas near the Galapagos Islands (Table 2, Figures 5a & 5b). Longlining was much more dispersed than squid jigging. Chinese squid jigging was concentrated in an equatorial band (approximately $5°S - 3°N$) to the west of the Galapagos Islands (Figure 5a). Remaining high industrial fishing activity in HDRs was all drifting longlines. A total of 308 Chinese longliners and 247 Taiwanese longliners fished the Western Pacific HDR in 2018 (Table 2, Figure 3b). Taiwanese drift longline activity by 120 vessels fished the Australasian HDR, focusing on Melanesia, southern New Guinea and Irian Jaya, and the northwest Australian shelf (Table 2, Figure 2b). More Taiwanese longline fishing targeted the Southern African HDR with 224 vessels, showing high activity to the east of the continent and the island of Madagascar (Table 2, Figure 4b). In short, high industrial fishing activity comprising 412 Chinese drift longliners, 344 Taiwanese drift longliners, 421 United States trawlers, and 331 Chinese squid jiggers, targeted High Diversity Regions worldwide in 2018. While the United States, China and Taiwan are not the only countries fishing HDRs, they operate the largest number of industrial fishing vessels.

3.3. Protected areas

The extensive spatial footprint of industrial fishing in high diversity areas, particularly by drift longline and tuna purse seine fleets, outlines important MPAs by effectively surrounding them. In the Western Pacific, the Phoenix Islands Protected Area (Kiribati), Pacific Remote Islands (U.S.), Palmyra Atoll (U.S.), Rose Atoll (American Samoa), and the Cook Islands Marine Park (Cook Islands) (Table 1) stand out as areas of low drift longline (Figure 3b) and tuna purse seine fishing activity (Figure 3a). In the Southern African HDR, the EEZs of South Africa, Somalia, the Comoro Islands, and the French administered islands of Mayotte, Juan de Nova, Bassas da India, and Isle Europa in the Mozambique Channel all show low drift longline fishing activity (Figure 4b). In Australasia, the Coral Sea Protected Area was an area of low fishing activity, bordered by high fishing activity to the south and east of New Guinea (Figure 2b). The Tasman Sea, the Kermadec, Norfolk Island, and Challenger Deep MPAs (all New Zealand) stand out as areas of low fishing activity (Figure 1b), as do the Lord Howe Island and Central Deep regions (Australia, Figure 2b). The fact that these MPAs are outlined by the spatial distribution of 2018 fishing hours data is both a testament to their protection, and a warning of encroaching fishing effort.

4. Discussion

Large ($> 100,000\ km^2$) Marine Protected Areas (MPAs) in High Diversity Regions (HDRs) are a relatively recent development. In several HDRs, protection has only been established in the last decade (since 2010). This is the case for the Norfolk Island and Lord Howe MPAs in the Tasman Sea, and for the Coral Sea, South-West Corner, and Argo-Rowley Terrace MPAs in Australasia, all established in 2012 (Table 1). The Mexican Revillagigedo and Pacifico Mexicano Profundo MPAs were established in 2017 and 2018 respectively (Table 1). British Pitcairn Island Reserve and Chilean Rapa Nui Park were both established in 2015 (Table 1). Marae Moana (Cook Islands) was established in 2012 and the Coral Sea Natural Park (New Caledonia) in 2014 (Table 1). Some conversions of parts of the EEZ of Seychelles into the Amirantes/ Fortune Bank MPA are still in process, projected for 2021. In the case of New Zealand, expansion of the Kermadec Islands MPA has been stalled by the political process.

In many cases, these MPAs have complex zonation with different types of fishing permitted in the different zones ((Costello and Ballantine, 2015)). For example, trawling may be excluded below a depth limit to protect habitat, which is the case below 800 m in the Pacifico Mexicano Profundo group of MPAs (Table 1). Areas where all fishing is prohibited (called "No Take" areas or Marine Reserves) can be a relatively small percentage of the MPA, even when the protected area is large. This is the case for the proposed New Zealand Kermadec Islands MPA (1% in a "No Take" Marine Reserve) and the Australian Lord Howe MPA (8% in a reserve) (Table 1. For the Caribbean Agoa Protected Area, New Caledonian Coral Sea Park, the Palau Sanctuary, and the Cook Islands Marae Moana, there are no fishing exclusion zones at all (Table 1), although the category of fishing permitted may vary. In Marae Moana for example, artisanal fishing is permitted everywhere, but industrial fishing is only permitted beyond a 50 mile radius of the Cook Islands.

The most extensive large MPAs are located in the Western Pacific ((Davies et al., 2017)). Cumulative impacts on large MPAs have been estimated to be higher than the global average ((Halpern et al., 2015)). The higher cumulative impacts measured for large MPAs are more due to climate-related factors rather than industrial fishing ((Davies et al., 2017)). However, the observation that large MPAs and some EEZs in the Tasman Sea, Australasia, Eastern Africa and the Western Pacific are surrounded by fishing activity suggests that these areas may be encroached upon in the future if enforcement regimes are inadequate to prevent it. Fishing the boundaries is already documented along the borders of some EEZs and MPAs. An example is the concentration of tuna purse seining along the Galapagos reserve boundaries, particularly in locations where tuna concentrate (Boerder et al., 2017).

Previous studies ((Kroodsma et al., 2018; Sala et al., 2018; Tickler et al., 2018b)) showed that China, Taiwan, South Korea, Japan, Indonesia and Spain are the nations dominating distant water industrial AIS-inferred effort. In this study, China and Taiwan dominated longline fishing in the HDRs, and China was responsible for virtually all of the squid jigging in the High Diversity Regions. There is little trawling by Asian fleets in the HDRs, and most trawling is carried out by countries of the regions (USA, South Africa, New Zealand), rather than by distant water fleets. The situation for tuna purse seining is more complicated because vessels flagged to many more countries are involved. However, it is known that flag states do not always reflect the nationality of the companies operating fishing vessels ((Carmine et al., 2020; Virdin et al., 2021)). In this study, I did not have information on flags of convenience or corporate ownership. It is also important to note that I excluded the East Asian HDR from my study due to problems with the data. In summary, High Diversity Regions on the high seas are exploited by distant water, mainly Chinese and Taiwanese drifting longline and squid jigging fleets, but these Asian fleets are not responsible for much of the trawling or tuna purse seine activity in the HDRs.

There are seven "No Take" areas larger than $100,000\ km^2$ worldwide in the High Diversity Regions, two in Australasia (Coral Sea Marine Reserve and the Great Barrier Reef World Heritage Area), one in Central America (Revillagigedo National Park), two in the Eastern Pacific (Pitcairn Islands Marine Reserve and Rapa Nui Marine Park) and two in the Western Pacific (Pacific Remote Islands and Phoenix Islands Protected Area, Table 1). The Southern African and Eastern Pacific HDRs have the highest proportion of their MPAs as "No Take" Marine Reserves (100% and 95% respectively) (Table 1). In contrast, the Tasman Sea HDR has 6% reserved, Central America 20% reserved, Australasia 26% reserved, and the Western Pacific 57% of the MPAs in HDRs classified as "'No Take' Marine Reserves (Table 1).

While the Western Pacific HDR experiences much higher drifting longline and tuna purse seine AIS-inferred effort than other HDRs (Figure 7), both previous work ((White et al., 2020)) and this study found that MPAs are generally areas of low industrial fishing activity. This is because large MPAs tend to be most often established in areas where fishing activity is low, but it is also because industrial fishing mostly exits areas that are declared protected ((White et al., 2020)).

Distant water fishing is operated by relatively few corporations. Carmine et al. (2020) reported that 100 corporate actors accounted for 36% of all high seas fishing effort in 2018. Since not all high seas effort occurs in High Diversity Regions, and vessels flagged to China and Taiwan are the most numerous in HDRs, it is reasonable to assume that even fewer corporate actors are responsible for most of the fishing effort in these regions. The current study shows that the greatest AIS-inferred effort in HDRs occurs in the Western Pacific and Southern African regions. The Western Pacific HDR encompasses the high seas regions around the EEZs of Micronesia, Papua New Guinea, Palau and Indonesia which is the area where the least is known about the corporate actors ((Carmine et al., 2020)). The Southern African HDR on the high seas to the east of the continent is a second area where little is known about the corporations fishing the region ((Carmine et al., 2020)). Drifting longliners were the most difficult to link to corporate actors, with 35% of fishing hours unable to be identified ((Carmine et al., 2020)). As we have shown, drifting longlines are the predominant gear type in terms of fishing activity in the Western Pacific and Southern African High Diversity Regions, which is consistent with the finding that drifting longlines are the predominant mode of fishing on the high seas globally ((Carmine et al., 2020; Sala et al., 2018)).

Drift longlining and tuna purse seining are the most profitable types of distant water fishing. These fishing methods are profitable in some regions even without fishing subsidies ((Sala et al., 2018)). They also reduce their labour costs by paying low wages to fishing crews ((McDonald et al., 2021; Sala et al., 2018; Tickler et al., 2018a)), often recruited from Indonesia or the Philippines to work on Chinese and Taiwanese fishing vessels (`https://'www'.theoutlawocean.com/reporting`, last accessed 11 May, 2021). Even with subsidies and low labour costs, drift longlining in areas like the Western Indian

Ocean to the north of Madagascar in the Southern African HDR are still not profitable for China and Taiwan ((Sala et al., 2018)). Chinese and Taiwanese longlining operations in the Western Pacific HDR and Eastern Pacific HDR make large losses, offset only by low labour costs ((Sala et al., 2018)), which lead to human rights abuses ((Sala et al., 2018)). China's squid fishing operations in the Eastern Pacific HDR are also unprofitable, except for the subsidized fishery beyond the Peruvian EEZ ((Sala et al., 2018)).

Sala et al. (2018) suggested that better fisheries management on the high seas might include reducing the size of fleets, innovative financing, marine reserves, and most importantly, subsidy reform. In the current study of High Diversity Regions, which are a subset of the high seas, the largest fleets are Chinese and Taiwanese, with drift longliners, tuna purse seiners and squid jiggers the major fishing gear types. The most heavily targeted regions are the Western Pacific and Southern African regions where companies operating vessels are the least well-known. This suggests that reducing the size of fleets, innovative financing, and subsidy reform could be complex and slow. More attention to Marine Protected Areas, as opposed to fleet capacity reduction and subsidy reform of Chinese and Taiwanese distant water fleets may offer a simpler and faster way to protect biodiversity.

5. Conclusions

A very positive observation in studies of the global high seas, and in the current study of High Diversity Regions, is that MPA boundaries are for the most part respected by distant water fleets. This means that MPAs, rather than "No Take" reserves may be sufficient to keep fishing efforts low in High Diversity Regions, provided that there is sufficient monitoring and transparency. Satellite monitoring of AIS-inferred effort will not be entirely sufficient because smaller vessels do not report AIS or VMS signals, and some vessels may turn off AIS signals. However, combining multiple monitoring methods ((Park et al., 2020)) of sufficiently large MPAs in High Diversity Regions holds considerable promise for protection of biodiversity from predation by distant water fishing fleets.

Focusing on monitoring and enforcement of MPAs places responsibility on the nations that established the MPAs (Table 1), rather than expecting the countries operating distant water fishing fleets to enact fleet capacity reforms and retract established subsidies in the near future. Nations like New Caledonia, Palau, Kiribati, Cook Islands, Seychelles, Mexico, Ecuador and Chile do not have sufficient resources to fully monitor and enforce large MPAs. Therefore it is the developed nations with interests in maintaining marine biodiversity that must step up to fund the monitoring and protection of large marine reserves. Real-time monitoring guiding targeted enforcement provides hope for protecting the High Diversity Regions of the world ocean from distant water fishing fleets, which admittedly is only one of the threats that they face in a changing climate.

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Competing interests and author contribution statements

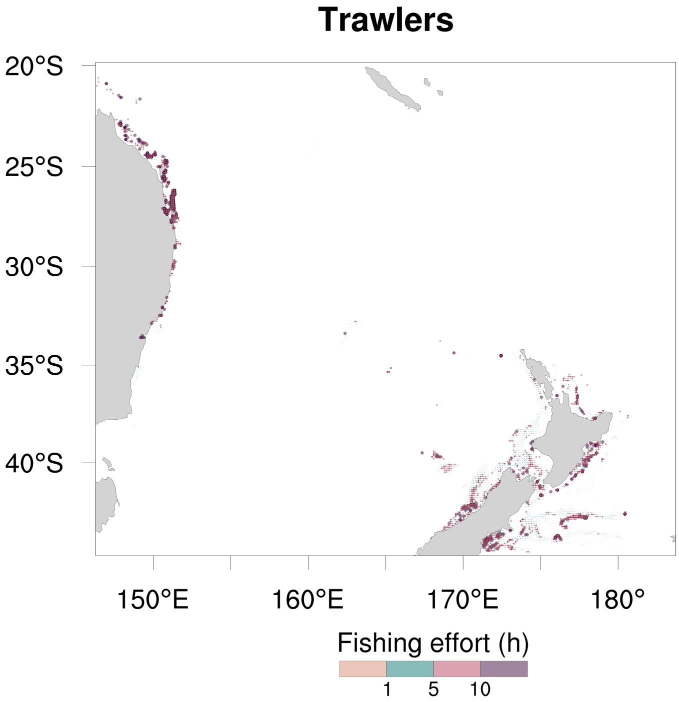
Sam McClatchie: Conceptualization, Software, Formal analysis, Investigation, Visualization, and Writing. There are no competing or conflicts of interests.

MPA	Nation	Year	Protected Area	"No Take" Area
Western Pacific			$\Sigma = 2,922,650\ km^2$	$\Sigma = 1,678,250\ km^2$
Pacific Remote Islands	United States	2009	$1,270,000\ km^2$	$1,270,000\ km^2$
Coral Sea Natural Park	New Caledonia	2014	$463,323\ km^2$	$0\ km^2$
Palau National Marine Sanctuary	Palau	2020	$457,077\ km^2$	$0\ km^2$
Phoenix Islands Protected Area	Kiribati	2008	$408,250\ km^2$	$408,250\ km^2$
Marae Moana	Cook Islands	2012	$324,000\ km^2$	$0\ km^2$
Eastern Pacific			$\Sigma = 1,703,834\ km^2$	$\Sigma = 1,613,334\ km^2$
Pitcairn Islands Marine Reserve	United Kingdom	2015	$834,334\ km^2$	$834,334\ km^2$
Rapa Nui Marine Park	Chile	2015	$740,000 km^2$	$740,000 km^2$
Galapagos Marine Sanctuary	Ecuador	1998	$129,500\ km^2$	$39,000\ km^2$
Australasia			$\Sigma = 1,752,678\ km^2$	$\Sigma = 448,291\ km^2$
Coral Sea Marine Reserve	Australia	2012	$989,842\ km^2$	$238,400\ km^2$
Great Barrier Reef World Heritage Area	Australia	1981	$345,000\ km^2$	$115,000\ km^2$
South-West Corner Marine Reserve	Australia	2012	$271,833\ km^2$	$58,841\ km^2$
Argo-Rowley Terrace Marine Park	Australia	2012	$146,003\ km^2$	$36,050\ km^2$
Southern Africa			$\Sigma = 210,000\ km^2$	$\Sigma = 210,000\ km^2$
Amirantes/ Fortune Bank	Seychelles	2021	$210,000\ km^2$	$210,000\ km^2$
Central America			$\Sigma = 727,084\ km^2$	$\Sigma = 147,629\ km^2$
Pacifico Mexicano Profundo	Mexico	2018	$436,147\ km^2$	Only below 800 m
Revillagigedo National Park	Mexico	2017	$147,629\ km^2$	$147,629\ km^2$
Agoa Specially Protected Area	Caribbean	2010	$143,308\ km^2$	$0\ km^2$
Tasman Sea			$\Sigma = 1,043,570\ km^2$	$\Sigma = 58,414\ km^2$
Kermadec Islands Marine Reserve	New Zealand	1990	$745,000\ km^2$	$7,480\ km^2$
Norfolk Island Marine Reserve	Australia	2012	$188,444\ km^2$	$41,661\ km^2$
Lord Howe Marine Reserve	Australia	2012	$110,126\ km^2$	$9,273\ km^2$

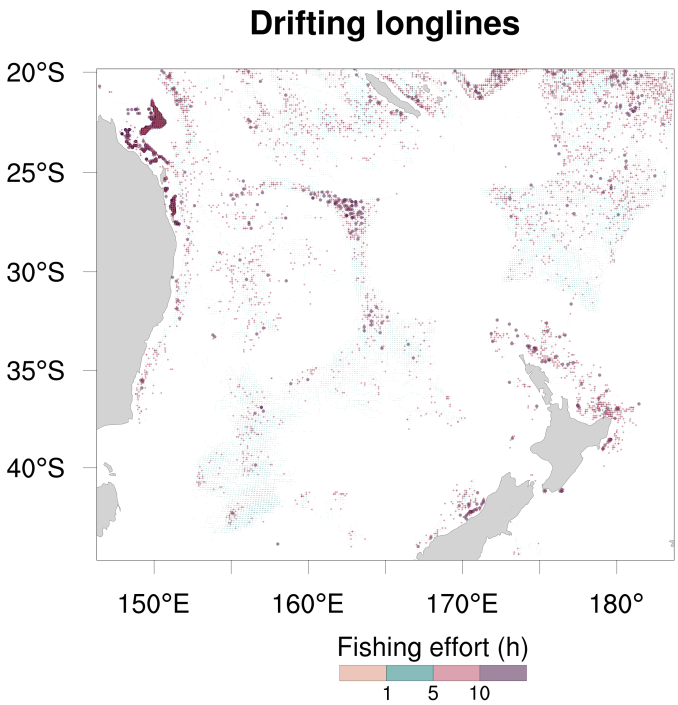
Table 1: Larger protection zones (area $> 100,000\ km^2$) in six High Diversity Regions (HDRs. Levels of protection from fishing vary from no take reserves excluding all types of fishing to licensed industrial fishing. Year indicates the year the reserve was established. Σ indicates the total protected area in each HDR.

Fleet size	Flag	Gear	Region
421	**USA**	**trawl**	**Central America**
3	ECU	trawl	Central America
1	FRA	trawl	Central America
17	ECU	tuna purse seine	Central America
16	MEX	tuna purse seine	Central America
13	VEN	tuna purse seine	Central America
331	**CHN**	**squid jigger**	**Eastern pacific**
5	TWN	squid jigger	Eastern Pacific
1	KOR	squid jigger	Eastern Pacific
104	**CHN**	**drift longline**	**Eastern Pacific**
69	TWN	drift longline	Eastern Pacific
50	JPN	drift longline	Eastern Pacific
30	USA	tuna purse seine	Western Pacific
25	TWN	tuna purse seine	Western Pacific
23	MEX	tuna purse seine	Western Pacific
308	**CHN**	**drift longline**	**Western Pacific**
247	**TWN**	**drift longline**	**Western Pacific**
92	KOR	drift longline	Western Pacific
26	JPN	tuna purse seine	Australasian
23	TWN	tuna purse seine	Australasian
23	PNG	tuna purse seine	Australasian
120	**TWN**	**drift longline**	**Australasian**
64	CHN	drift longline	Australasian
57	JPN	drift longline	Australasian
63	ZAF	trawler	Southern Africa
40	NAM	trawler	Southern Africa
28	GHA	trawler	Southern Africa
224	**TWN**	**drift longline**	**Southern Africa**
66	CHN	drift longline	Southern Africa
49	JPN	drift longline	Southern Africa
55	NZL	trawler	Tasman Sea
36	AUS	trawler	Tasman Sea
1	VGB	trawler	Tasman Sea
55	CHN	drift longline	Tasman Sea
35	AUS	drift longline	Tasman Sea
35	FJI	drift longline	Tasman Sea

Table 2: Industrial fishing activity ranked by the top three flag states for the two most common gear categories in each High Diversity Region. Industrial fishing activity involving more than 100 vessels is highlighted. Country codes: AUS Australia, CHN China, ECU Ecuador, FRA France, FJI Fiji, GHA Ghana, JPN Japan, KEN Kenya, KOR Korea, MEX Mexico, NAM Namibia, NZL New Zealand, PNG Papua New Guinea, TWN Taiwan, USA United States, VEN Venezuela, VGB Virgin Islands, ZAF South Africa

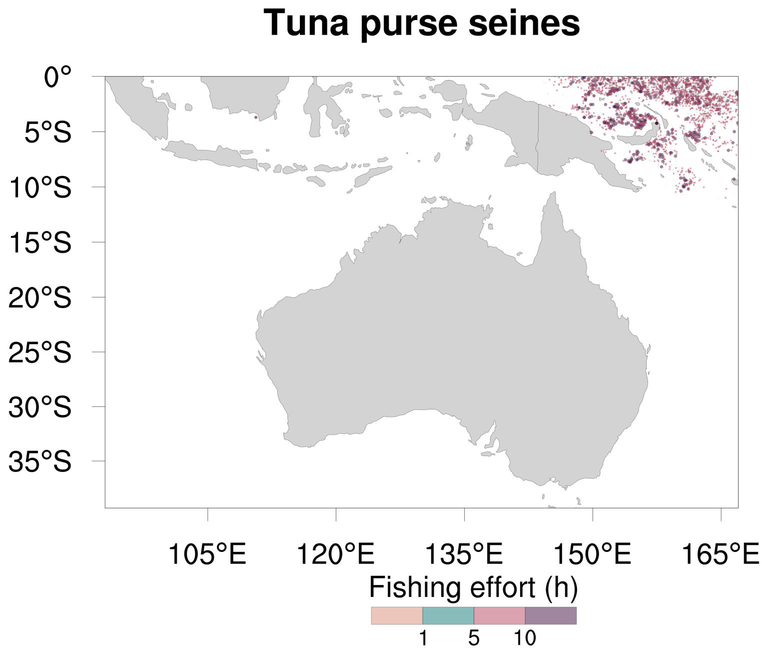


(a)

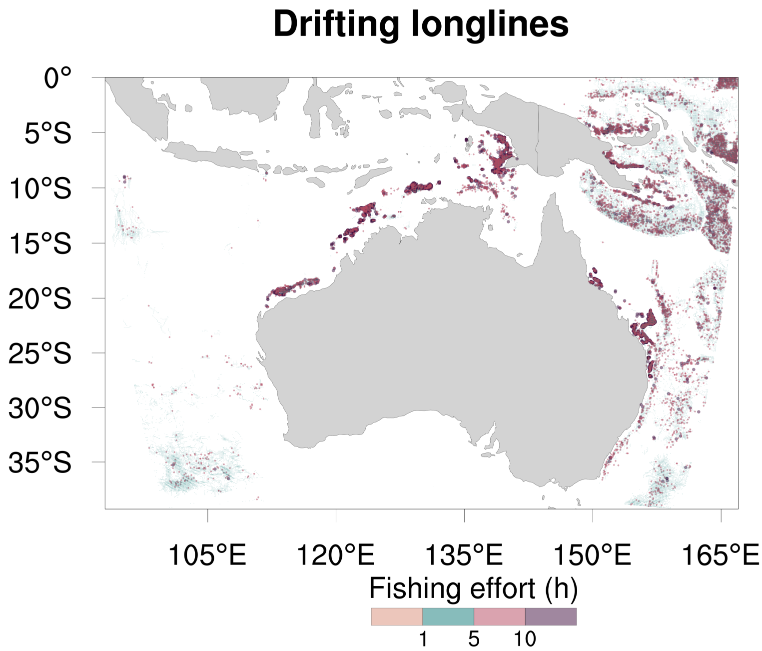


(b)

Figure 1: (print in colour) Spatial distribution of AIS-inferred effort identified as (a) trawlers or (b) drifting longlines during 2018 in the Tasman Sea High Diversity Region.

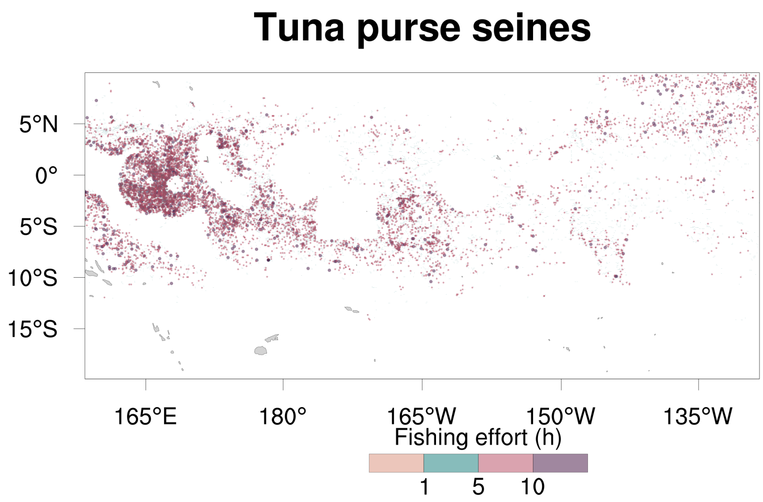


(a)

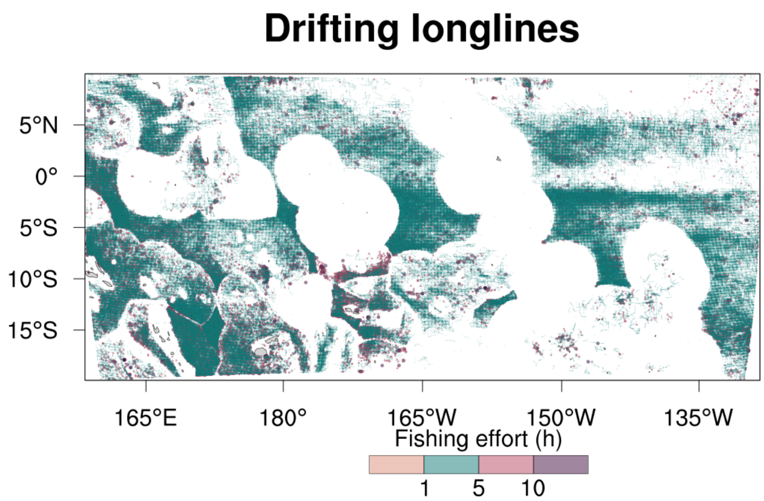


(b)

Figure 2: (print in colour, single column width) Spatial distribution of AIS-inferred effort identified as (a) tuna purse seines or (b) drifting longlines during 2018 in the Australasian High Diversity Region.

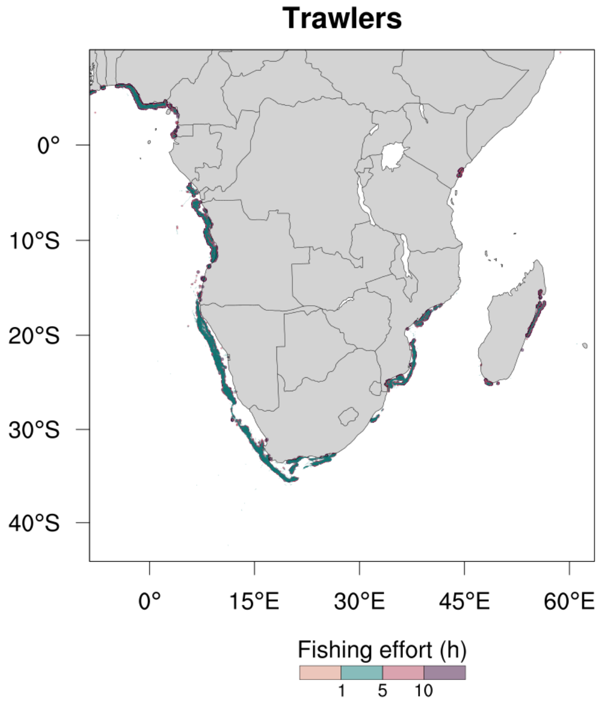


(a)



(b)

Figure 3: (print in colour, single column width) Spatial distribution of AIS-inferred effort identified as (a) tuna purse seines or (b) drifting longlines during 2018 in the Western Pacific High Diversity Region.



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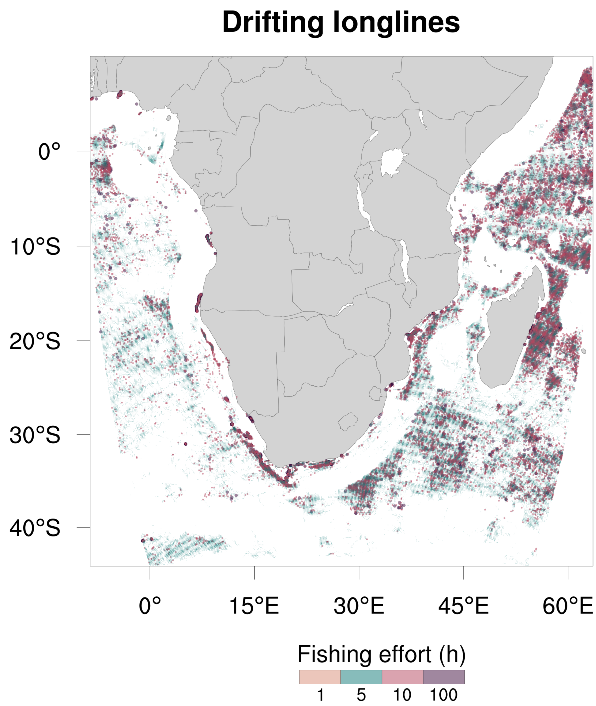
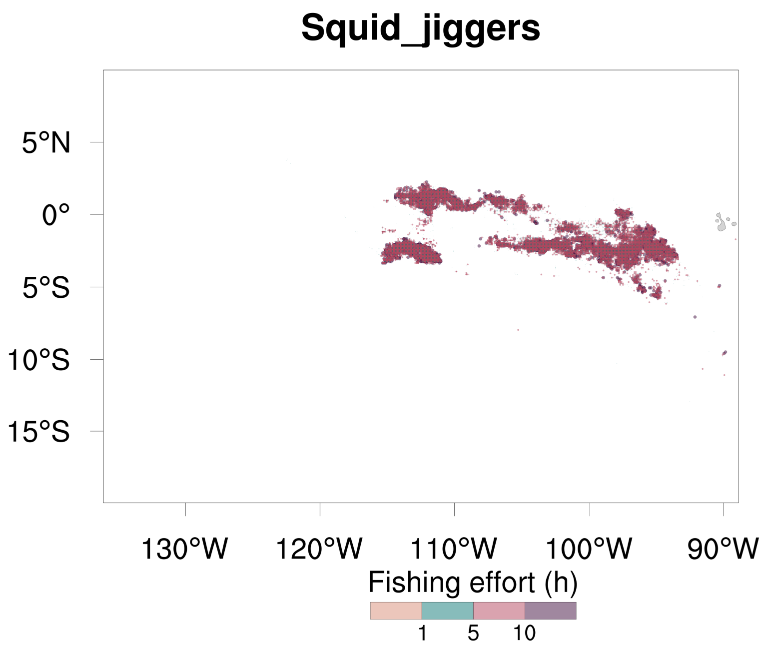
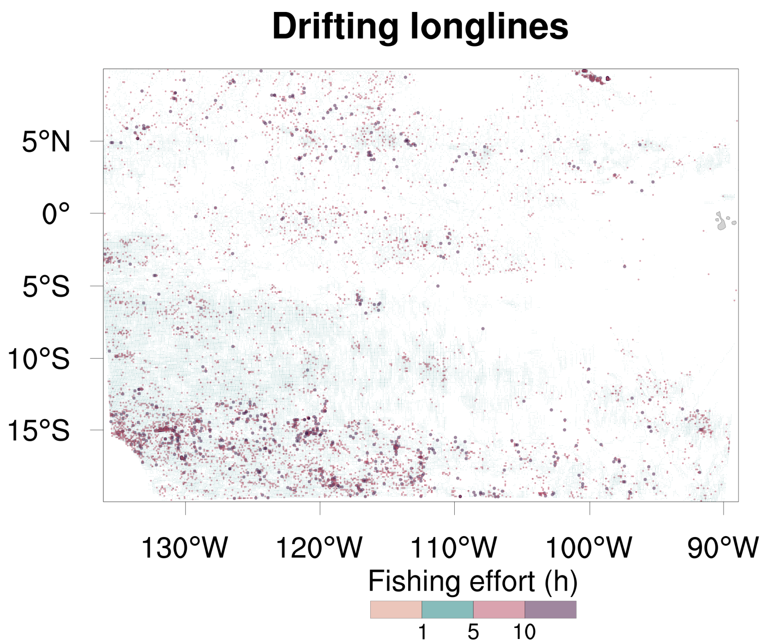


(b)

Figure 4: (print in colour, single column width) Spatial distribution of AIS-inferred effort identified as (a) trawlers or (b) drifting longlines during 2018 in the Southern African High Diversity Region.

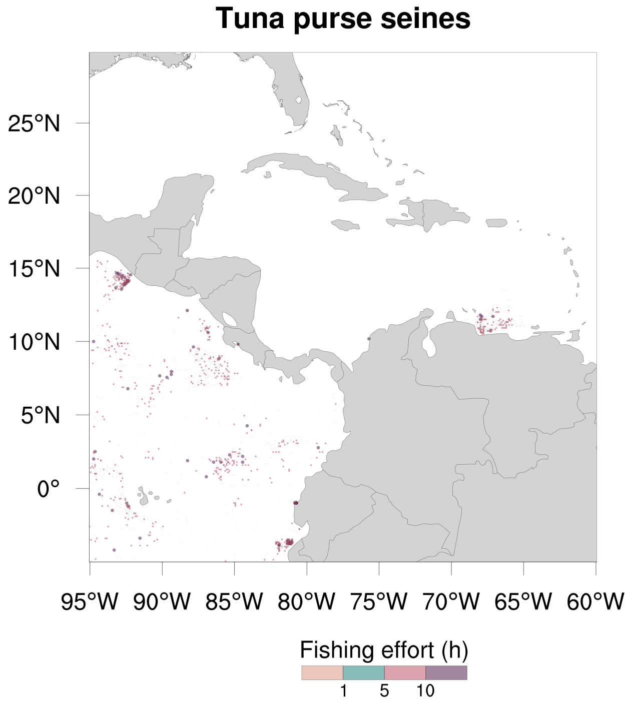


(a)



(b)

Figure 5: (print in colour, single column width) Spatial distribution of AIS-inferred effort identified as (a) squid jiggers or (b) drifting longlines during 2018 in the Eastern Pacific High Diversity Region.



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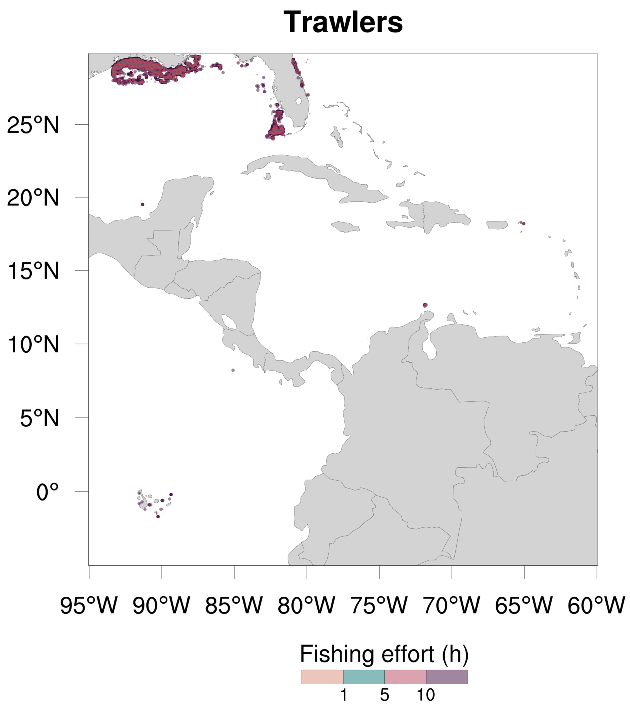

(b)

Figure 6: (print in colour, single column width) Spatial distribution of AIS-inferred effort identified as (a) tuna purse seines or (b) trawlers during 2018 in the Central America High Diversity Region.

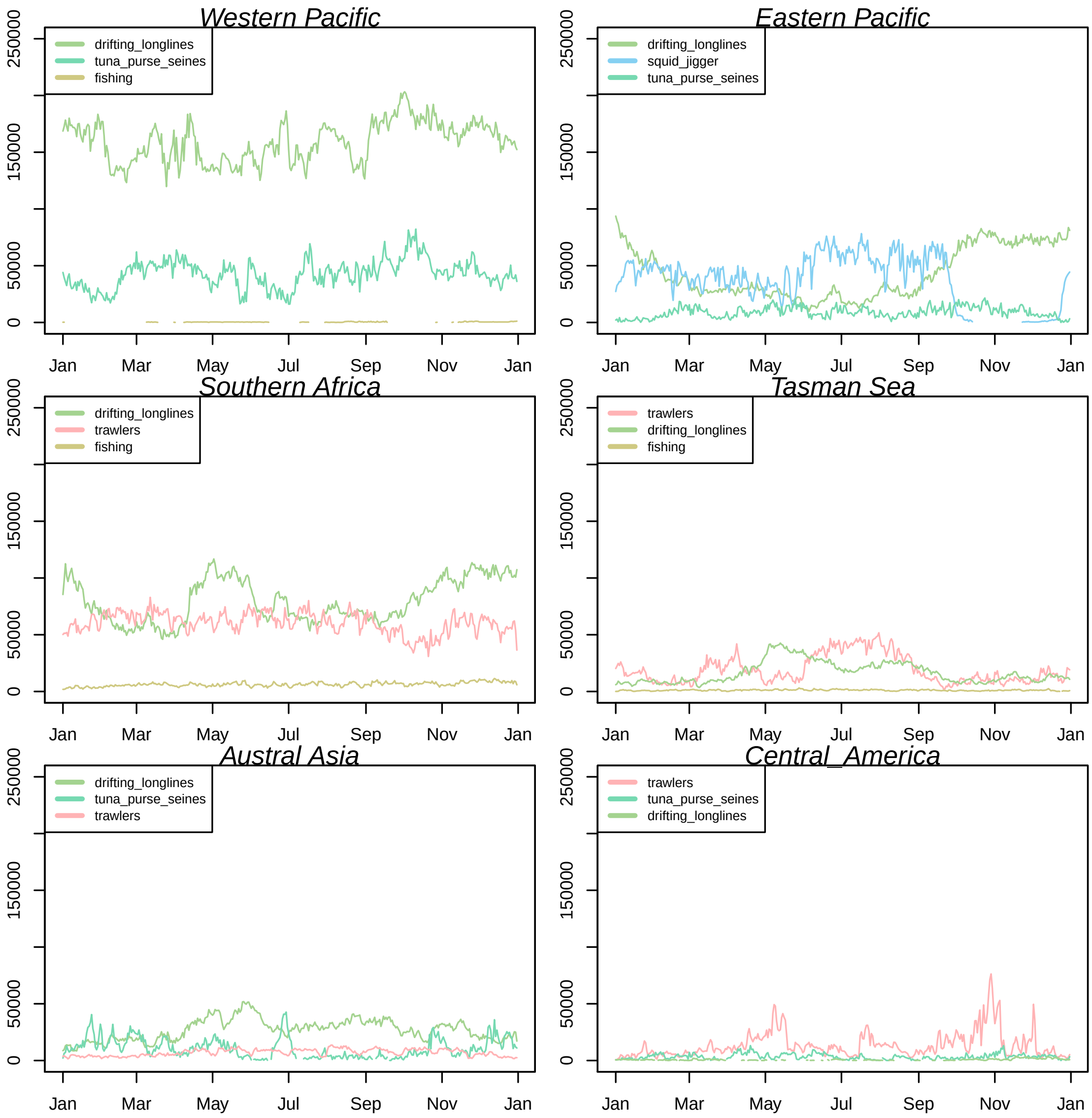

Figure 7: (print in colour, two column width) Fishing effort in 2018 ($kW\ day^{-1}$, calculated by multiplying time spent fishing by vessel power) for the three gear types showing highest AIS-inferred effort for each region. Unidentified gear type is labeled "fishing". Note different scale ranges for effort.