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Tracking industrial fishing activities in African waters from space

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Abstract

Marine fisheries in African waters contribute substantially to food security and local economies in African coastal nations. Recently, there are growing concerns about the sustainability of living marine resources in these countries' exclusive economic zones (EEZs) due to increased risks from climate change, pollution and potential over-exploitation of fisheries resources by non-African (foreign) countries. To effectively manage fishing activities and sustain marine resources in African waters, we need useful tools for characterizing the fishing activities in African waters. Here, we assess the utility of the Automatic Identification System (AIS) derived data for describing the spatial characteristics of African and foreign industrial fishing activities within the EEZs of African coastal nations. The results show that the AIS-derived spatial pattern of industrial fishing activities in African waters is consistent with that of industrial catches derived from the Sea Around Us database. Across African EEZs, the spatial correlations between primary productivity and fishing effort highly vary by gear types, which emphasizes the importance of investigating specific fishing strategies when studying the effects of bottom-up drivers on fishing effort. We find an EEZ-specific spatial pattern for fishing efforts across African waters and identify some socioeconomic, political and geographic factors that likely affect the decision of fleets to fish in specific African EEZs. We conclude that AIS-derived fishing data can be a useful complementary tool for characterizing the spatial pattern of industrial fishing efforts in African waters.

KEYWORDS

African fisheries, automatic identification system, exclusive economic zone, fishing gear, primary productivity, spatial pattern

1 | INTRODUCTION

The exclusive economic zones (EEZs) of African countries are rich in fish resources, with total marine fisheries catches over 6 million tonnes, contributing 15 billion USD to African gross domestic product in 2011 (de Graaf & Garibaldi, 2014; Food & Agriculture Organization, 2014). Three of the four most productive marine ecosystems in the world are adjacent to Africa, including the Canary current, Benguela current and Somali coastal current upwelling systems (Rosenberg et al., 2014). Fisheries in Africa consist of a wide range of artisanal and industrial fishing (Alder & Sumaila, 2004; Lakhnigue et al., 2019) and account for over 50% of the total intake of animal protein for many coastal communities in Africa (Belhabib et al., 2015; Food & Agriculture Organization, 2014). African waters are also important fishing grounds for global seafood supply through trade and distant-water fishing (Alder & Sumaila, 2004; Belhabib, Sumaila, Lam, et al., 2015; Pauly et al., 2014).

Previous studies have raised concerns that foreign fishing in African waters may outcompete domestic fisheries and over-exploit fisheries resources in West Africa (Atta-Mills et al., 2004; Belhabib, Sumaila, & Pauly, 2015; Mallory, 2013). Foreign industrial fleets, initially from Europe and later East Asia, have greatly expanded the distribution and intensity of fishing effort in African waters since the 1950s (Alder & Sumaila, 2004; Rosenberg et al., 2014; Seto, 2015; Tickler et al., 2018). Growing seafood demand coupled with the overexploitation and depletion of some local fish stocks in some European and Asian waters have further driven foreign fleets to fish not only the high seas off the coast of Africa but also the EEZs of African countries (Alder & Sumaila, 2004; Andriamahefazafy et al., 2020; Belhabib et al., 2020; Froese et al., 2018; Kaczynski & Fluharty, 2002; McCauley et al., 2018; Shen & Heino, 2014). At present, quantitative assessments of fishing activities conducted by both African and foreign fleets in African waters are limited.

The recent applications of automatic identification system (AIS) data provided promising opportunities for tracking spatially explicit fishing activities in regions with limited traditional fisheries monitoring (Arias & Pressey, 2016; Kroodsma et al., 2018). AIS was initially developed for preventing vessel collision, and it tracks the geographic location of individual vessels at high spatial resolution in near real time (McCauley et al., 2016). AIS equipment was installed on almost all fishing vessels larger than 300 gross tons, and it became widely adopted for many smaller vessels (International Maritime Organization, 2003; Kroodsma et al., 2018). Kroodsma et al. (2018) compiled and processed billions of AIS messages received since 2012 to build a Global Fishing Watch (GFW) database that tracks the fishing footprint of individual vessels. This database, which contains the majority of active fishing vessels larger than 24 m, has enabled novel investigation into spatiotemporal patterns of fishing activities in global high seas (Kroodsma et al., 2018; Sala et al., 2018), African inshore waters (Belhabib et al., 2020) and marine protected areas (Dureuil et al., 2018; Lynham et al., 2020).

However, to date, very few studies evaluated the applicability and potential biases of AIS-derived measures of fishing effort in regions that have limited data in fisheries and ecological properties. In this study, we aim to investigate the utility of AIS-derived fishing data for characterizing fishing patterns in the African EEZ. We categorize fishing vessels into domestic and foreign vessels, with the former being flagged to African countries and the latter to non-African countries. We describe spatial variability in fishing effort within and across EEZs and between foreign and domestic industrial fishing vessels. We explore the factors that may have led to the observed spatial variability of fishing effort, including fishing gears, biophysical factors (e.g. NPP, bottom depth, distance to shore) and socioeconomic factors (e.g. geographic proximity, local fisheries status). We also characterize the spatial pattern of fisheries catches drawn from *the Sea Around Us* (SAU) database and compare it with our AIS-derived fishing pattern in order to evaluate the compatibility between the two.

2 | MATERIALS AND METHODS

2.1 | Fishing time and location

Global Fishing Watch had computed the distribution of AIS-tracked fishing vessels at a high temporal and spatial resolution by using the AIS data that recorded the position and direction of the vessel at 2-s to 3-min time intervals (Guiet et al., 2019). We obtained fishing time data gridded at 0.5°latitude × 0.5°longitude within EEZs of 41 African maritime countries and territories from the GFW database (available at https://globalfishingwatch.org/datasets-and-code/fishing-effort/). Fishing time was measured as the number of hours spent fishing at the geolocation represented by the distance from shore of the coastal state, and we use fishing time as a proxy for fishing effort and use these two terms interchangeable throughout this paper. We also extracted information related to fishing vessel identity (e.g. vessel length, gear type, flag state).

2.2 | Fisheries catches in African waters

We extracted the fisheries catch data from African waters during 2012–2016 from the *Sea Around Us* (SAU) reconstructed catch database, which was constructed by using a wide variety of data and information sources to derive estimates for all fisheries components missing from the official reported data (Pauly & Zeller, 2015, 2016). This catch database aims to incorporate unreported catch including catches from subsistence and recreational fishing sectors, discards, and in some cases, illegal, unreported and unregulated (IUU) fishing, which, by definition, are not part of official national data reported to the FAO. The time series catch data (2012–2016) are allocated to 0.5° x 0.5° grid cell using the spatial allocation method, and each catch record is associated with the gear type, fishing sectors, fishing entity, fishing location and year (Zeller et al., 2016).

Since most foreign fishing fleets in African waters were considered industrial-scale fisheries, we assume that these fleets are mostly equipped with AIS in this study. The length of African fishing fleets identified by the AIS data in this study (mean: 36 m, range: 12–138 m) resembles that of non-African industrial fishing fleets (mean: 42 m, range: 10–146 m) (Figure S1). Thus, the AIS data largely unrepresented the many small African vessels (2–24 m) that were known to operate in African waters (Belhabib et al., 2018; Christ et al., 2020). We therefore counted the AIS-detected African fishing as industrial fishing activity in this study. To compare with the spatial patterns of both African and non-African fishing, we used annual industrial catch data in each grid cell of the African waters from 2012 to 2016 by five gear types (i.e. pelagic trawl, bottom trawl, longlines, gillnets, purse seine). When comparing spatial patterns between AIS-derived fishing effort and SAU-derived fisheries catch, pelagic and bottom trawl in SAU were combined as trawlers and AIS-detected drifting and set longlines were combined as longlines.

2.3 | Net primary production (NPP) and bathymetry data

To quantify the primary production of African waters, remote sensing products were gathered. We used the estimates of NPP available through the Oregon State University (http://sites.science.oregonstate.edu/ocean.productivity/eppley.model.php). These NPP was estimated based on remote sensing data from the MODIS aqua satellite from 2002 to 2018 and processed using the eppley-VGPM algorithm (Behrenfeld & Falkowski, 1997). The collected data were then averaged at an annual time scale and regridded over a 0.5° spatial grid. We also used the bathymetry data within African EEZs extracted from NOAA's National Centers for Environmental Information Global Relief Model (https://ngdc.noaa.gov/mgg/global/global.html).

2.4 | Data analysis

We summed the AIS-detected fishing hours of individual vessels by gear type, EEZ and flag state to provide descriptive statistics of fishing flag states and their geographic distribution in Africa. Many biophysical, socioeconomic and political factors likely all play a role in driving the spatial preference of fishing activities across African EEZs. We conducted multivariate linear regression to investigate the main explanatory factors for the AIS-detected fishing time at a given location within African waters (e.g. nautical mile away from shore) (N = 35,678), including NPP, gear type, the distance to shore, the mean bottom depth at each fishing location and the EEZ the fishing location belongs to. Following the default setting (alphabetical order) in R version 3.4.1(R Core, 2018), we used Drifting Longlines and Angola EEZ as the reference levels for categorical variables Gear type and EEZ, respectively. The test assumptions for linear regressions (i.e. normality, linearity, heteroscedasticity, multicollinearity) were checked by scatterplots, histograms, QQ plots and variance inflation factor, and the fishing time was log-transformed to satisfy all these assumptions. We discussed how some socioeconomic and political factors that are endogenous to the quantitative analysis may affect the results and conclusions in Section 4.2.

To evaluate the extent to which the AIS-derived spatial fishing pattern reflects fishing activities known from AIS-independent information sources, we examined the correlation between the AIS-derived mean fishing location and the SAU-derived catch centroid across African EEZs. The mean fishing location is the fishing hours-weighted mean of all individual fleet's fishing distances from shore in each African EEZ (Equation 1). The catch centroid is the catch-weighted mean of the distance from shore and is used to indicate the geographic centroids for catches in each African EEZ (Equation 2).

$$\text{Mean fishing location} = \sum_{i=1}^{n} \frac{i \times \text{Fishing hours}_i}{\text{Total fishing hours in the EEZ}} \quad (1)$$

$$\text{Catch centroid} = \sum_{i=1}^{n} \frac{i \times \text{Catch}_i}{\text{Total Catch in the EEZ}} \quad (2)$$

$$\text{NPP centroid} = \sum_{i=1}^{n} \frac{(i \times \text{NPP}_i)}{\text{Total NPP in the EEZ}} \quad (3)$$

Where i is the fishing distance to shore (nautical mile); n is the farthest distance to shore within a specific EEZ ($n \leq 200$ nautical miles); Fishing hours$_i$, Catch$_i$ and NPP$_i$ are the fishing duration, total catches and NPP at i nautical mile from the shore, respectively.

Many socioeconomic and political factors (e.g. fishing permit) that we could not account for in the multivariate linear regression may lead to high variability in spatial preference of fishing activities across African EEZs and obscure the relationship between marine productivity and fishing locations. To further investigate how the spatial pattern of AIS-detected fishing activities is associated with marine productivity across fishing gear types within a given African EEZ, we examined the correlation between the NPP centroid and the mean fishing location of specific fishing activities (trawlers, drifting longlines and purse seines) conducted by African fleets and non-African fleets, respectively. The NPP centroid is the NPP-weighted mean of the distance to shore and is used to indicate the spatial pattern of primary productivity in each African EEZ (Figure S2; Equation 3). The relationships between NPP centroid and mean fishing location by other fishing activities were not tested due to their small sample sizes. All statistical analyses were performed using R version 3.4.1 (R Core, 2018).

3 | RESULTS

3.1 | Industrial fishing patterns by flag states across African EEZs

Our analysis used AIS-derived fishing data to characterize the key identity and spatial components of industrial fishing activities in African waters, including fishing flag states, fishing locations and gear types. Between 2012 and 2016, we recorded fishing activities in African EEZs operated by vessels flagged by 74 countries and territories from all continents except Antarctica. Non-African flagged vessels spent longer time to fish than African flagged ones, responsible for 60% of recorded total domestic and foreign fishing time in African waters (Table 1). Activities of foreign fishing fleets flagged in Europe and Asia account for 27% and 30% of total fishing time. In contrast, fishing fleets from the Americas and Oceania together only account for 4% of total fishing time in African waters. At the country level, foreign fishing in EEZs of African countries carried the flags, largely, of Spain (13% of the total recorded fishing time), Taiwan (11%) and Italy (9%), followed by Japan (8%) and China (7%) (Table 1). African nations are responsible for 40% of total fishing time recorded in African waters, and South Africa is the main fishing countries, accounting for 14% of the total fishing time, followed by Morocco (7%), Ghana (4%) and Namibia (4%) (Table 1).

The top nine foreign flagged states that spent most time fishing in African waters also exploited a wide geographic range for fishing. All of them fished in more than 10 EEZs in Africa, but the spatial distributions of their fishing activities vary considerably across flag states (Figure 1). Vessels flagged in China, Spain and Russia primarily fished in West Africa (e.g. Mauritania, Angola, West Sahara), while Japanese, Taiwanese and Korean flagged fishing vessels operated mainly in southeast Africa (e.g. Mozambique) and offshore islands (e.g. Madagascar, Mauritius). Italian fishing predominantly occurred in the waters of Tunisia. St. Vincent & the Grenadines and Belize are ranked 8 and 9 in the list of major foreign fishers in African EEZs, and they are open registry states (aka. Flags of Convenience) whose fleets are primarily foreign-owned (Asariotis et al., 2009) (Table 1). Their spatial fishing patterns reveal the foreign owners of Belize, and St. Vincent & the Grenadines fleets have a strong interest in fishing in Western Saharan and Namibian waters, respectively (Figure 1).

Compared with widespread fishing operations by foreign vessels, the detected African flagged vessels show much more concentrated spatial fishing patterns in African waters. The majority of African countries only exploited their domestic waters and/or the EEZs of nearby countries (Figure 2). In fact, 96% of South Africa's fishing time happened in its own EEZ. Morocco, Réunion, Comoros and Ghana are the major African fishers that also spent a considerable amount of time for distant-water fishing, mostly in their nearby EEZs. The only exception is Comoros, an archipelago off Africa's east coast and an open registry state (ITF House, 2020), which spent most of its fishing time in the water off West Africa (Figure 2).

As a result of varying degrees of foreign fishing across African EEZs, the number of flag states that operated within each African country's EEZ ranged from 1 to 33 (Figure 3a). The EEZs fished by a large number of countries are generally located in West Africa. For example, the EEZs of Western Sahara and Mauritania in Northwest Africa were fished by the highest numbers of flag states (32 and 33, respectively) (Figure 3a). Among all African EEZs, South Africa and Madagascar were fished for the longest time for different reasons; South Africa's EEZ is mostly exploited by domestic fishing while Madagascar's water is primarily fished by foreign fleets (Figure 3b,c).

3.2 | Spatial distributions of AIS-detected fishing time

For both non-African and African flagged fishing in African waters, trawling vessels tend to fish close to shore (0–100 nm from the nearest coastline) while drifting longline fleets distributed more evenly across the whole EEZ (0–200 nm) (Figure 4). All non-African flagged trawling time happened within 100 nm from shore and 86% of trawling within 50 nm in contrast to that only 56% of drifting longline fishing time happened within 100 nm from shore. African flagged drifting longline and trawling vessels illustrate similar spatial distribution to that of non-African flagged fishing, with drifting longline fleets spending 72% of time within 100 nm from shore and 81% of trawling time occurring within 50 nm from shore. More descriptive statistics regarding the fishing time across gear types can be found in Table 2

At a given location of African waters ($N = 35,678$), among all factors that we used to explain the amount of AIS-detected fishing time in Table 3, EEZ of the fishing location and gear type is the major factors responsible for the variability in total, foreign and African fishing time. After accounting for NPP, EEZ, distance to shore, depth and gear type, non-African flagged fleets spent 35% more time in African waters than those African industrial fishing fleets (Table S1). Compared with Angola's EEZ (default reference level) and controlling for all other variables, the EEZs of Morocco, Namibia, Saint Helena and South Africa have significantly higher fishing time by African flagged vessels, while the EEZs of Cape Verde, Madagascar, Mozambique, Mauritania, Mauritius and Seychelle are fished significantly longer by non-African flagged vessels (p-value <.001). Detailed parameter estimates for all variables can be found in Table S1.

TABLE 1 The number of vessels and fished EEZs, and fishing time of each fishing flag state in African waters between 2012 and 2016

Flag states	No. of vessels	No. of fished EEZs in Africa	Fishing time (hr)	The fraction of total fishing time in African waters (%)
Non-African states				
Spain	233	33	5.75E + 05	12.5
Taiwan	209	17	4.95E + 05	10.8
Italy	276	14	4.06E + 05	8.8
Japan	73	19	3.61E + 05	7.9
China	117	27	3.06E + 05	6.7
South Korea	45	24	1.48E + 05	3.2
Russia	31	14	6.69E + 04	1.5
St. Vincent & Grenadines	8	6	5.68E + 04	1.2
Belize	30	22	5.11E + 04	1.1
France	37	25	4.41E + 04	1.0
Malaysia	5	4	3.68E + 04	0.8
Portugal	37	19	3.10E + 04	0.7
Netherlands	10	8	2.38E + 04	0.5
Greece	8	8	2.28E + 04	0.5
Others	146	–	1.41E + 05	3.1
Subtotal	1,265	–	2.76E + 06	60.2
African states				
South Africa	218	12	6.60E + 05	14.4
Morocco	52	4	3.36E + 05	7.3
Ghana	67	6	1.86E + 05	4.0
Namibia	33	6	1.61E + 05	3.5
Réunion	23	7	1.36E + 05	3.0
Senegal	18	12	1.07E + 05	2.3
Angola	11	2	5.94E + 04	1.3
Comoros	11	7	5.41E + 04	1.2
Seychelles	34	8	4.31E + 04	0.9
Mozambique	17	1	2.97E + 04	0.6
Mauritania	4	2	2.16E + 04	0.5
Others	41	–	3.45E + 04	0.8
Subtotal	529	–	1.83E + 06	39.8
Total	1,794	–	4.59E + 06	100

3.3 | Spatial patterns of AIS-derived fishing activities versus fisheries catches and NPP

We found the AIS-derived mean fishing location can explain the majority of the variability in the SAU-derived catch centroid within an African EEZ. We observed significant correlations between catch centroid and the mean location of both non-African and African flagged fishing (R^2 = .80 and .74, respectively). Similar and consistent correlations were observed across 2012–2016 (Figure S4). In addition, the AIS-derived mean location of all three types of fishing activity is closely associated with the centroid of the corresponding catch estimated based on the SAU database and the relationship is close to a 1:1 ratio (Figure 5).

We also found significant correlations between NPP centroid and the mean location of both non-African and African flagged fishing and across 2012–2016 (Figure S5 and S6). Gear type and NPP centroid together dictate where the non-African fishing activities occurred, explaining 82% of the variability in mean fishing location (Table S2). The mean location of African or non-African fishing activities does not vary significantly across years (p-value >.05). The NPP centroid is closely related to the locations of foreign drifting longline fishing across EEZs (R^2 = .68, p-value <.001), to less extent, explains foreign purse seine fishing locations (R^2 = .41, p-value <.001) (Figure 6). Compared with non-African fishing, the mean fishing location of African country flagged vessels is less related to gear type and NPP centroid (R^2 = .43; Table S2). The purse seine is the only

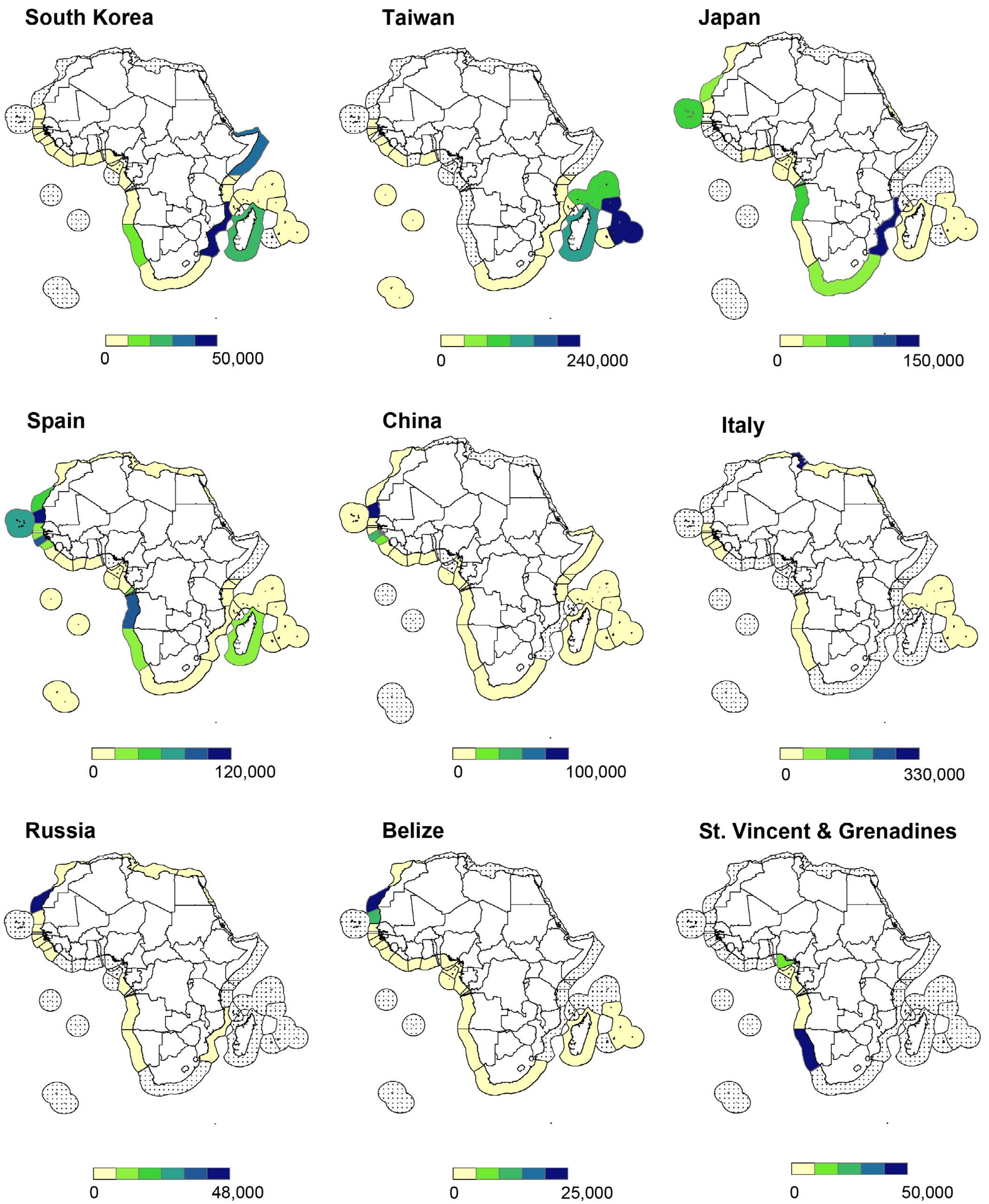

FIGURE 1 The spatial distribution of fishing effort (hr) by nine major non-African flagged fishing entities operating in African waters. The colour bar signifies the range of fishing hours and is divided using equal interval classification. The stippled areas are the EEZs where AIS did not detect any fishing activity by the specified fishing state between 2012 and 2016

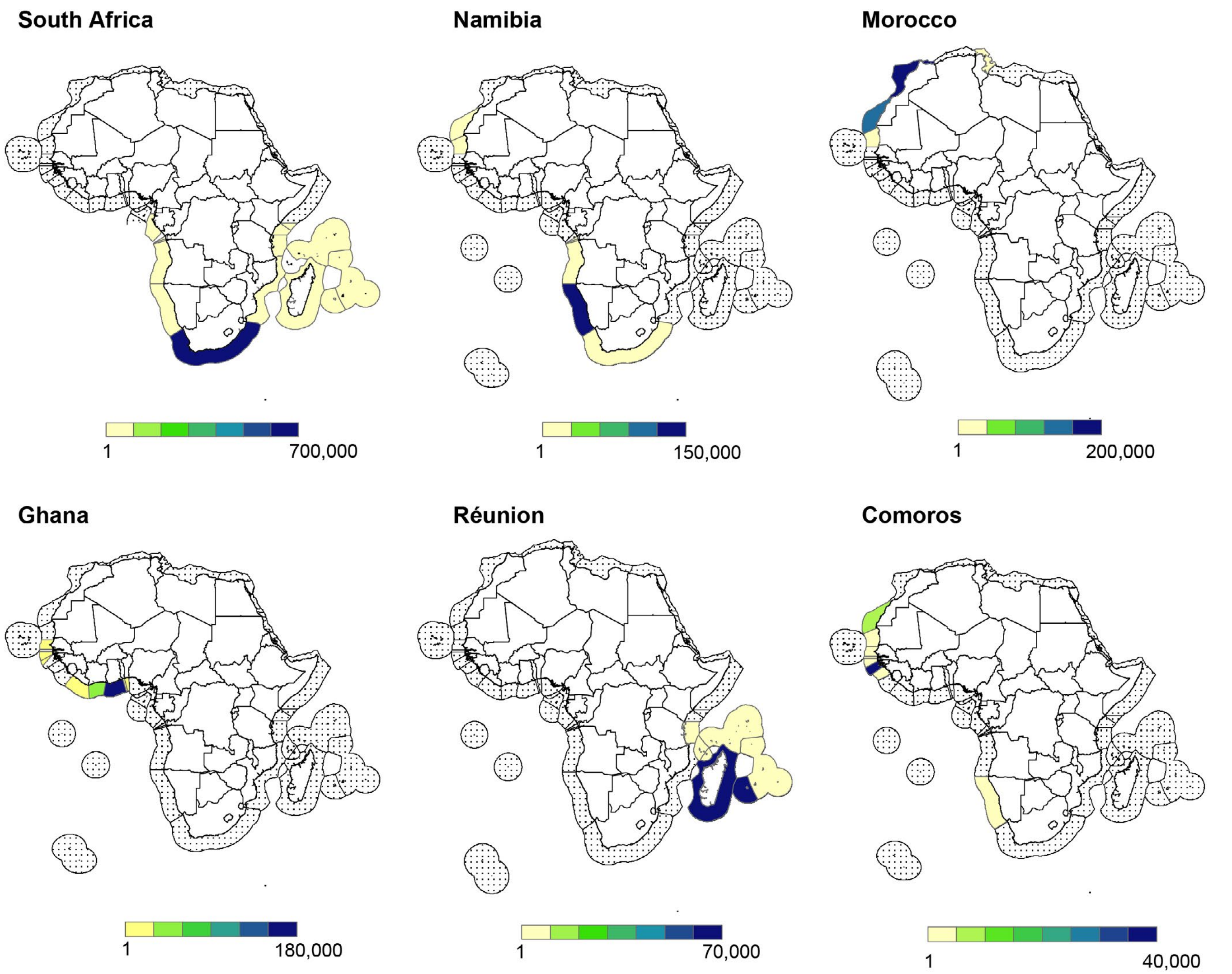

FIGURE 2 The spatial distribution of fishing effort (hr) by six major African fishing states. The colour bar signifies the range of fishing hours and is divided using equal interval classification. The stippled areas are the EEZs where AIS did not detect any fishing activity by the specified fishing state between 2012 and 2016

gear type that illustrates a significant correlation between fishing location and the NPP centroid (Figure 6). The NPP cannot explain foreign or African trawler fishing locations (*p*-value >.05; Figure 6). We elaborate on the potential reasons that cause the disparity in correlations between foreign and African fishing and across gear types in the discussion.

4 | DISCUSSION

4.1 | Automatic identification system data provide means of understanding fishing patterns in African waters

Our analysis shows that non-African flagged vessels from all over the world fish in African waters and the composition of foreign industrial fleets resemble those consisting of global industrial fishing efforts (Tickler et al., 2018) and high-seas fishing (Kroodsma et al., 2018; Sala et al., 2018). The mean fishing locations of foreign and African fishing activity align well with the central location of catches of the EEZ, demonstrating the consistency in the spatial pattern between AIS-derived fishing effort and fisheries catches from Sea Around Us. Although the AIS-derived fishing data likely miss some fishing effort by African and foreign vessels that do not carry or switch off AIS equipment, our results indicate that AIS data can provide a complementary and reliable means for characterizing the spatial characteristics of major industrial fishing activities in African waters and imply that the industrial fishing effort missed by AIS is either a very small fraction or has spatial patterns similar to the one described here.

Our study suggests the potential of using multiple data sources, including the AIS-detected fishing footprint and the SAU catch database, to help identify unreported and potential illegal fishing in the region. Belhabib et al., (2019) showed that most fish stocks in the Canary Current and the Benguela Current large marine ecosystems

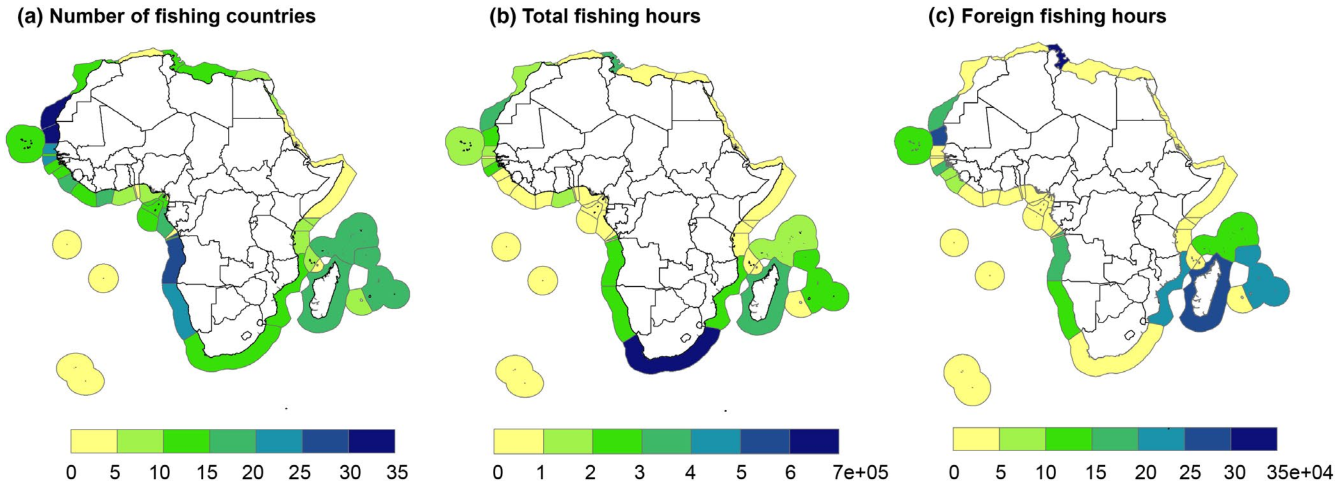

FIGURE 3 Characteristics of fishing activities in the EEZs of African coastal nations and territories between 2012 and 2016, including (a) the number of fishing countries (b) the number of fishing hours by all fleets, and (c) fishing time exploited by foreign fleets. The colour bar signifies the data range and is divided using equal interval classification

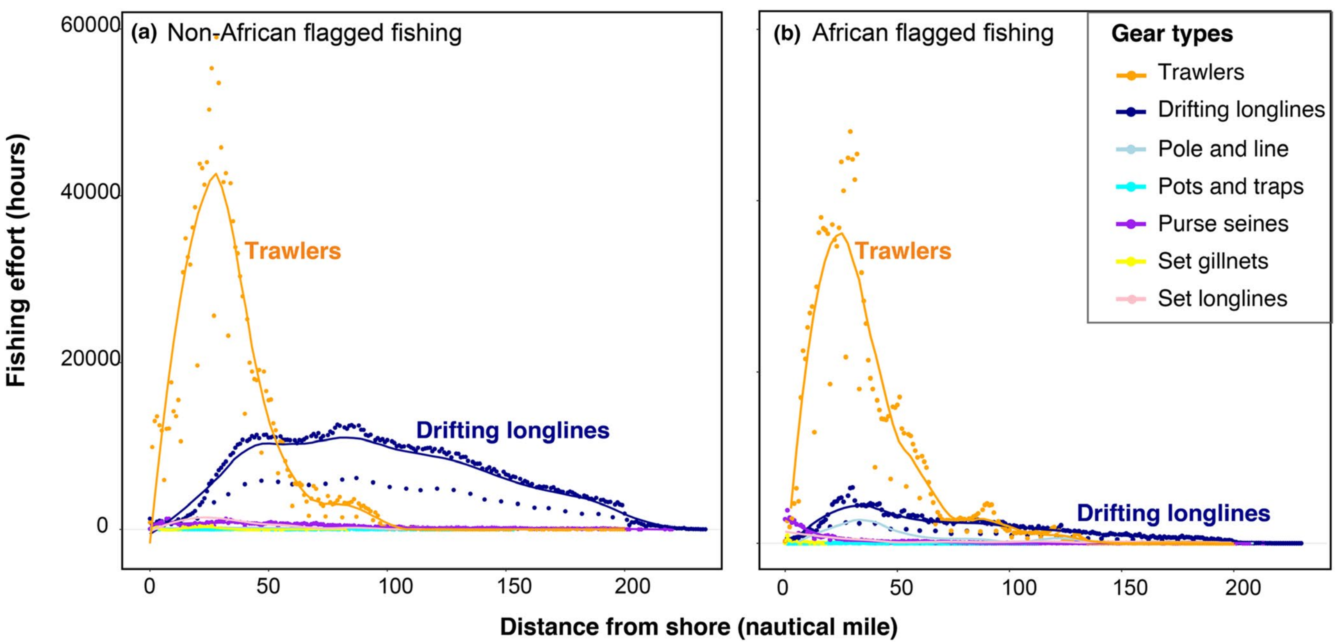

FIGURE 4 The distribution of total fishing time (hr) of (a) non-African flagged and (b) African flagged fishing activities across distance from the nearest coastline by different gear types. Each dot represents the aggregated fishing time by a specific type of fishing that happened within each nautical mile from shore. We used geom_smooth function in R with loess method (span = 0.3) to plot smooth lines of these data

are either fully or over-exploited, largely due to intensive legal and illegal industrial fishing. These regions are also identified in our study as generally the most popular fishing grounds for industrial fishing fleets, including many flagged to open registry states. Although some of the coastal countries in these regions (e.g. Namibia) require the fleets fishing in their EEZs to land all catches at their domestic landing ports (Sumaila et al., 2004), we find that some fishing fleets did not follow the regulation, which would result in under-estimation of catches. For example, our study identified 20 fishing entities in Namibian waters from the AIS records, but not all of the AIS-detected fishing flag states were recorded as having catches in Namibian waters based on the SAU catch database. Specifically, St. Vincent & the Grenadines flagged fleets spent longest time among all foreign flag states in Namibian water, but their catch was not recorded in SAU database, neither was for other open registry states like Comoros and Belize. Given that Namibia has one of the few relatively well-managed fisheries in the world (Sainsbury & Sumaila, 2003; Sumaila et al., 2004), it is likely that similar unreported fishing occurs in many other African EEZs. Our results indicate the potential utility of AIS vessel tracking data for detecting and characterizing unreported activities, thus providing

TABLE 2 The number of vessels and the distribution of fishing time conducted by non-African vs. African flagged fleets across gear types

Gear type	Non-African flagged No. of vessels	Non-African flagged Fishing hours (%)	African flagged No. of vessels	African flagged Fishing hours (%)
Trawlers	537	1.4E + 06 (50.3%)	248	1.30E + 06 (68.5%)
Drifting longlines	499	1.2E + 06 (44.5%)	102	3.4E + 05 (18.4%)
Purse seines	132	6.3E + 04 (2.3%)	107	4.4E + 04 (2.4%)
Set longlines	48	5.6E + 04 (2.0%)	16	4.7E + 04 (2.6%)
Pole and line	16	1.4E + 04 (0.5%)	47	1.1E + 05 (5.9%)
Set gillnets	7	4.9E + 03 (0.2%)	4	2.3E + 03 (0.1%)
Pots and traps	4	1.8E + 03 (0.1%)	2	9.4E + 02 (0.1%)
Squid jigger	21	1.6E + 02 (0.01%)	0	0 (0%)
Tug	0	0 (0%)	1	2.3E + 04 (1.3%)
Others	1	4.1E + 03 (0.1%)	2	1.3E + 04 (0.7%)
Total	1,265	2.8E + 06 (100%)	529	1.8E + 06 (100%)

TABLE 3 Summary results (p-value, proportion of variation explained by a certain variable) of multivariate linear regressions for explaining log-transformed all, foreign and African fishing time (hr) between 2012 and 2016 in African waters

Variables	$\log_{10}$ (Total fishing time) *p*-value	$\log_{10}$ (Total fishing time) Explained variation (%)	$\log_{10}$ (Foreign time) *p*-value	$\log_{10}$ (Foreign time) Explained variation (%)	$\log_{10}$ (African time) *p-value*	$\log_{10}$ (African time) Explained variation (%)
Gear type	Table S1	16.5	Table S1	17.3	Table S1	26.0
EEZ	Table S1	10.0	Table S1	26.0	Table S1	8.8
NPP	<.001	0.1	<.001	0.5	.001	0.1
Distance to shore	<.001	2.0	<.001	0.8	<.001	5.4
Bottom depth	.769	0.0002	.029	0.2	.342	0.6
Foreign entity	<.001	1.4	–	–	–	–
Year	<.001	0.21	<.001	0.03	<.001	1.1
Total R^2	–	.30	–	.45	–	.42

Note: The explained variation (partial R^2) is estimated using analysis of variance. Detailed coefficient estimates can be found in Table S1.

essential information for developing national and international responses to address IUU fishing in African waters in general.

4.2 | Drivers for the AIS-derived spatial fishing patterns in African waters

Our analysis illustrates that fishing time occurred at a given African location highly depends on the specific EEZ that the location belongs to. This EEZ-specific pattern cannot be attributed to physical and biogeochemical factors examined in this study, including marine productivity, distance to shore and bottom depth of the fishing location. We attribute this EEZ-specific fishing pattern to different socioeconomic and political conditions of African nations. The EEZs of African nations that have developed a relatively strong fishing industry tend to be fished longer by African countries, primarily by the domestic fishing. For example, Morocco, Namibia and South Africa, which restricted foreign fishing permits in their EEZs and put the effort in developing local fisheries, have fished longer in African waters, principally in their own EEZs (FAO, 2001; Guénette et al., 2001; Sumaila et al., 2004). In contrast, the thriving large-scale tuna and billfish fishing in the western Indian Ocean likely explains the elevated non-African fishing activities in the waters of Madagascar, Mauritius and Seychelle (Andriamahefazafy et al., 2020; Breuil & Grima, 2014).

The legal accessibility of the EEZ is a key factor to differ the spatial pattern of foreign fishing effort across African EEZs. Under the United Nations' Convention on Law of the Sea, foreign countries require a fishing permit to access fisheries in the EEZ of other countries (United Nations, 1982). Western African nations with abundant fishery resources often have agreements with foreign countries, allowing them to exploit marine resources in exchange for development aid and financial and infrastructure compensation (Belhabib, Sumaila, Lam, et al., 2015). This explains why their EEZs have large numbers of fishing entities and long foreign fishing time (Figure 3). Also, geographic vicinity can play an important role in determining

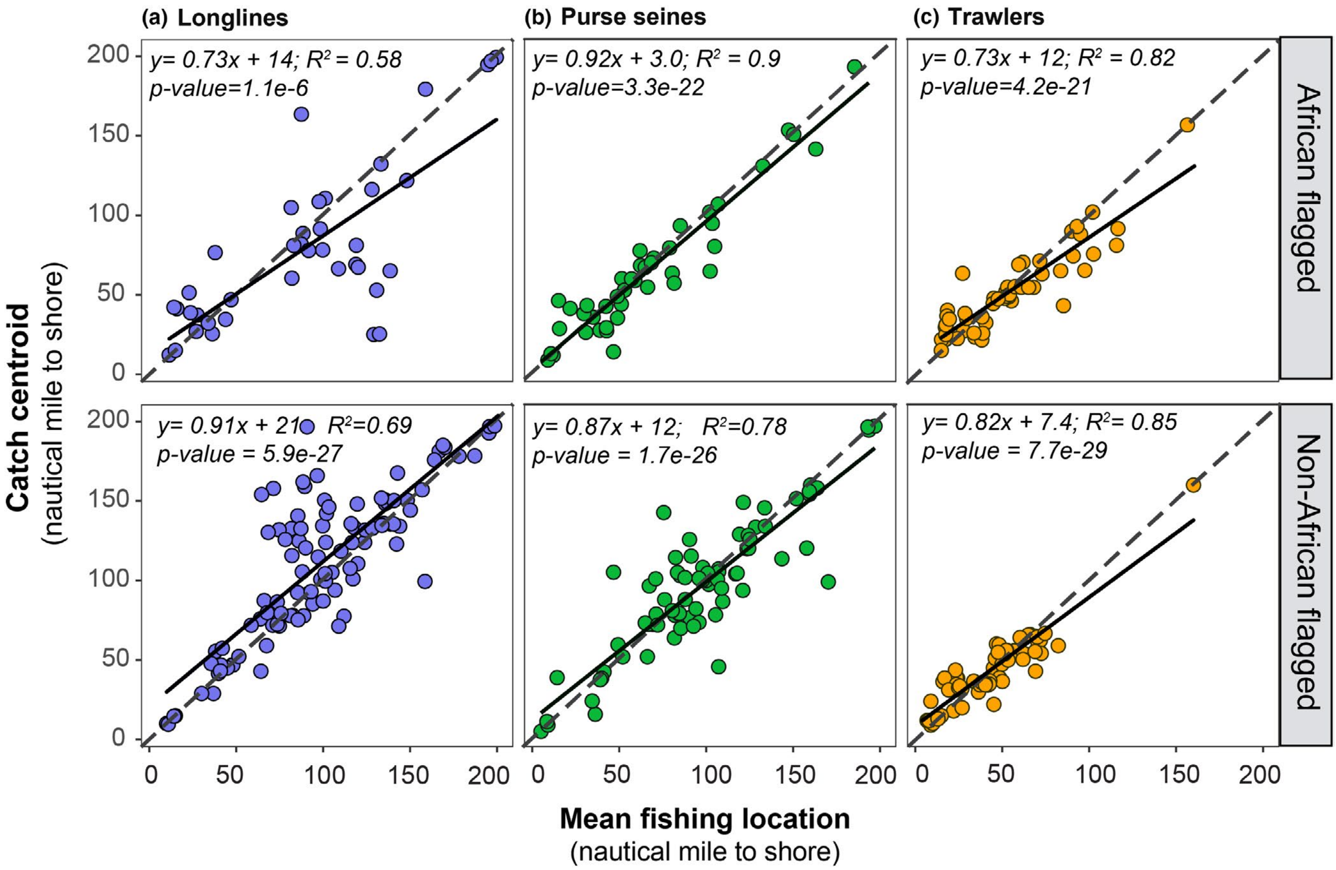

FIGURE 5 The relationships between the SAU-derived catch centroid and the AIS-derived mean fishing location of (a) Drifitng longlines; (b) Purse seines; (c) Trawlers conducted by non-African vs. African countries flagged fleets. The solid and dashed lines signify the simple linear regression line and the 1:1 line, respectively. The calculation of the mean fishing location and the catch centroid is elaborated in Methods

which African EEZs fishing entities choose to fish in. For example, almost all Italian fishing efforts occurred in Tunisian waters, which makes Tunisian EEZ has particularly high foreign fishing time. Fishing nearby also applies to many African countries that only fish in nearby EEZs in addition to their domestic water; for instance, the dominant fisher in Madagascar's water is its neighbouring entity Réunion (Figure 2).

The distribution of specific fish stocks (e.g. tuna) could largely affect the geographic distribution of the vessels that target these highly valued species. For instance, even though the productivity is generally higher on the west coast of Africa, the majority of fishing effort from Japan occurs in East Africa, which largely results in the long foreign fishing time in certain areas of southeast Africa (Figure 3c). Coulter et al. (2020) found that the southwest Indian Ocean, which encompasses Madagascar, Réunion, Seychelle and Mauritius, becomes increasingly important fishing grounds for tuna. Previous reports also showed that tuna and tuna-like species are the main targeted species by distant-water fleets from Asia and Europe in the EEZs of Mozambique and Madagascar (Breuil & Grima, 2014; United Nations, 2017). We estimated based on SAU data that tuna catches account for 75% of total Japanese catches in the waters of Madagascar, Mauritius, Mozambique and Seychelle, confirming that the spatial pattern of Japanese fishing activities identified from the AIS records corroborate with the productivity of the Indian Ocean tuna fisheries.

The AIS-based analysis also recorded a substantial amount of fishing activities in East Africa by South Korean and Taiwanese fleets. However, their tuna catches account for less than 10% of their total catches in East Africa, which implies that fishing activities by these two countries targeted non-tuna species or that their tuna catches were under-estimated in the SAU database. Additional research with species information other than tuna and potential unreported tuna catches estimates that are independent of the SAU data will help elucidate the discrepancy between patterns of fishing activity indicated by SAU and AIS databases.

4.3 | The sensitivity of spatial fishing patterns to marine productivity

Kroodsma et al. (2018) previously showed the low sensitivity of global fishing patterns to environmental variables. In this study, we find the spatial correlation between marine productivity and fishing effort highly depends on gear types, probably related to the distribution

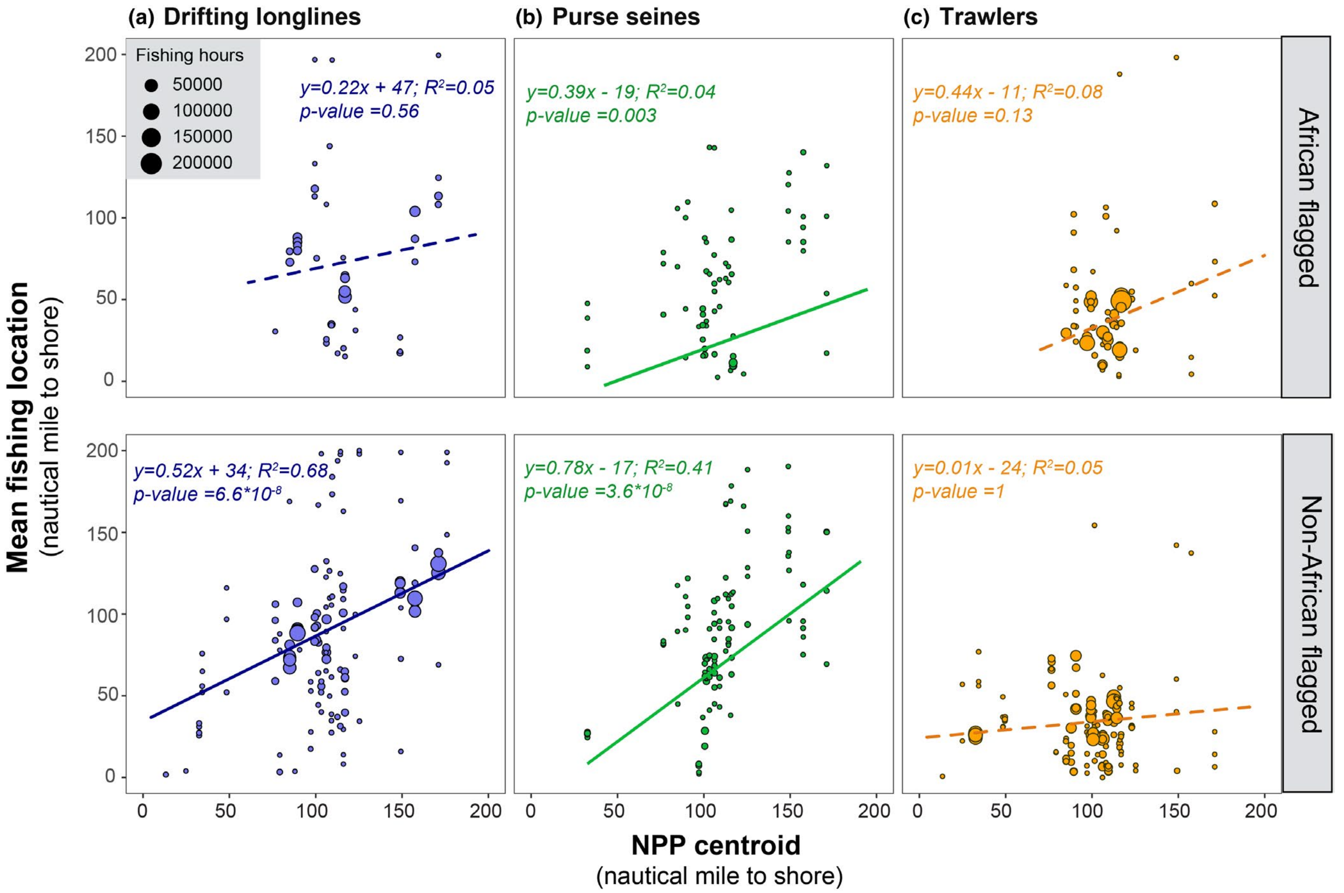

FIGURE 6 The relationships between the NPP centroid and the AIS-derived mean fishing location of (a) Drifitng longlines; (b) Purse seines; (c) Trawlers conducted by non-African vs. African countries flagged fleets. The dot size corresponds to the number of fishing hours, and some dots may be overlapped. The statistics and equations are based on weighted linear regression (weight = fishing hours). Significant relationships (*p*-value <.05) are indicated with solid lines, and insignificant relationships are illustrated in dashed lines, respectively. The calculation of the mean fishing location and the NPP centroid is elaborated in Methods

of species targeted by different fishing strategies. Drifting longline and purse seine fishing often target pelagic species, and the spatial distribution of these fishing fleets is closely related to primary production. Trawlers fishing effort does not follow the spatial pattern of NPP in African waters and trawling fleets predominantly fish in coastal areas (<50 nautical miles) where the mean bottom depth is within 670 m (Figure S3). We attribute this lack of spatial correlation between marine productivity and trawling fishing activities to the nature of bottom trawling.

Based on SAU catch data, bottom trawling plays a dominant role in African waters, producing more than three times of fisheries catch than that of pelagic trawling in 2012–2016. As bottom trawling targets species that rely on the benthic food web, their fishing practice follows the spatial distribution of benthic fish and invertebrates and is often constrained within the continental shelf (Watling & Norse, 1998). Consistent with our findings, prior studies found that the most important factors for explaining the distribution of benthic fishes and invertebrates are photosynthetically active radiation, temperature, bottom depth, salinity, oxygen and substrate of the seafloor (e.g. sand, reef, seagrass), rather than primary productivity (Fanelli et al., 2013; Galaiduk et al., 2017; Mazor et al., 2021). Here, we cannot rule out the influence of the relatively less accurate estimation of NPP in coastal waters where high loads of dissolved organic matter may be interpreted as chlorophyll *a* by satellites (Sathyendranath & Morel, 1983). Future studies with multiple indicators of biological productivity and more environmental variables will help further elucidate the relative contribution of bottom-up drivers in affecting trawling fishing efforts in African coastal waters.

The overall weaker correlations between NPP centroid and mean fishing location of African flagged fleets relative to that of non-African ones reflect that the African flagged vessels may not exploit the productive areas (Figure 6). Elucidating the exact reasons for African fleets not fishing in most productive grounds is beyond the scope of this paper, but we hope our findings could motivate future research to investigate a range of potential reasons, such as fuel cost, fishing technology and conflict avoidance. Such information will help African governments and international organizations prioritize their financial and technical resources to enhance African local fisheries.

5 | CONCLUSION

The traditional methods for analysing fishing efforts and catches are primarily based on global fishing vessel registries and self-reported fishing data from the Food and Agriculture Organization of the United Nations. However, the detail and accuracy of these data are highly variable across regions and countries, and inadequate information and misreporting frequently occur (Anticamara et al., 2011; Belhabib et al., 2014, 2016). In this study, we analyse AIS-derived fishing data to generate a quantitative assessment of the industrial fishing footprint in African waters. The AIS-derived spatial pattern of industrial fishing activities in African waters is consistent with that of industrial catches derived from the SAU database, which indicates that the AIS-derived fishing data can be a complementary tool to provide a broad view of fishing effort across African waters. The results suggest that jointly assessing the AIS tracking data and the SAU catch data can provide new insight into unreported and potentially illegal fishing activities.

Crespo et al. (2018) previously showed that the fishing effort of global pelagic longline fleets can be predicted by a variety of environmental variables (e.g. primary productivity and surface temperature). Our results provide additional evidence that the spatial correlations between marine productivity and fishing effort highly vary by gear types, and fishing efforts that primarily target pelagic species are much more related to ecosystem productivity relative to those fish benthic species. Therefore, jointly assessing a wide range of fishing strategies would likely miss the importance of environmental variables on fishing effort.

A better understanding of factors driving occurrences of foreign and domestic fishing in African waters can provide useful insights into effective spatiotemporal management strategies at both national and regional levels. Here, we find that AIS-detected fishing effort at a given location of African waters depends on which EEZ the fishing practice occurs. This EEZ-specific fishing pattern is significant after accounting for biophysical and fishing factors, such as gear type, ecosystem productivity, bottom depth and distance to shore. Based on the observed spatial variability of fishing effort across African EEZs, we infer that the capacity of domestic fisheries, the legal accessibility of an EEZ, geographic vicinity and biogeography of targeted fisheries likely all play an important role for a flag state in selecting specific African EEZs to fish. As the major fishers in African waters are similar to those in global fishing activities, we expect some of these factors may help explain the spatial distribution of industrial fishing in other fishing grounds over the world.

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DATA AVAILABILITY STATEMENT

All Global Fishing Watch Data are available online. Data on the main findings of this study are available from the corresponding author upon request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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