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Catching industrial fishing incursions into inshore waters of Africa from space

Dyhia Belhabib[1] | William W. L. Cheung[2] | David Kroodsma[3] | Vicky W. Y. Lam[2] | Philip J. Underwood[2] | John Virdin[4]

[1]Ecotrust Canada, Vancouver, BC, Canada

[2]Nippon Foundation-UBC NEREUS Program, Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, BC, Canada

[3]Global Fishing Watch, Washington, DC, USA

[4]Nicholas Institute for Environmental Policy Solutions, Duke University, Durham, NC, USA

Correspondence
Dyhia Belhabib, Ecotrust Canada, 90 - 425 Carrall Street, Vancouver, BC V6B 6E3 Canada.
Email: dyhia.belhabib@gmail.com

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Abstract

Small-scale fisheries contribute substantially to the sustainability of coastal communities by providing livelihood and economic opportunities and ensuring food security. However, their geographic range of operation overlaps with that of industrial fisheries, increasing the resource competition, risk of vessel collision and inter-sector conflicts, while jeopardizing the sustainability of fish stocks. When industrial vessels venture into waters that are reserved to artisanal fisheries, their operations become illegal. In Africa, the extent of such operations, beyond their legal implications, has resulted in severe economic, food security and maritime safety issues. In this paper, we use automatic identification system data derived from satellite technology to predict fishing operations and find that industrial fleets spend 3%–6% of their time fishing within inshore areas reserved for small-scale fisheries between 2012 and 2016, of the total 4.2 million industrial fishing hours within the Exclusive Economic Zones of African countries. We assessed the total fishing effort by this form of illegal fishing operations at 166 million kWhours at least out of 4.9 billion kWhours in total. We discuss this dangerous form of illegal fishing, which often results in deadly collisions with small-scale sector operators, increases competition and conflicts over fisheries access, threatens the sustainability of fish stocks, and calls for better governance, and protection.

KEYWORDS

African waters, Artisanal fishing zones, automatic identification system, illegal fishing, large-scale fisheries, small-scale fisheries

1 | INTRODUCTION

In Africa, marine small-scale fisheries (SSF), a form of fishing conducted typically from shore or on small fishing boats using low technology and low capital by coastal communities, contribute substantially to the livelihood, income and food security of coastal communities (Belhabib, Sumaila, Lam, et al., 2015). The contribution of African small-scale fisheries to the total catch by all sectors is particularly higher than the global average contribution of SSF to the total catch in other regions of the world, with a quarter (23%) of the 13 million tonnes of catches coming predominantly from African inshore waters (Belhabib et al., 2016). In contrast, catches from industrial fishing in Africa are mostly owned and operated by international fishing companies or in joint ventures with domestic companies, and the catch is commonly traded in international markets (Alder & Sumaila, 2004; Belhabib, Sumaila, Lam, et al., 2015). The majority of the industrial-scale fishing vessels operating in African waters, besides the domestic fleets, are flagged to The People's Republic of China and the European Union (Belhabib, Sumaila, Lam, et al., 2015).

Fishing grounds for SSF in Africa are often explicitly defined in the national legislation within which industrial-scale fishing is limited or prohibited. Out of 33 African states considered here, 30 have designated an area for inshore fishing, while all states have set fishing capacity limitations to manage industrial fishing access within their waters (Doumbouya et al., 2017). These areas include "inshore exclusion zones" (IEZs; INTERPOL, 2014), "artisanal fishing zones" (AFZs) and other types of coastal management zoning that excludes industrial fishing (Mora et al., 2009; Roberts, Hawkins, & Gell, 2005). These areas are located between 3 and 24 nm from the coast line and the objectives of their designation include conservation of fish stocks and protection of marine ecosystems for the interest of their national fisheries, food security and the reduction of accidents at sea and inter-sectoral conflicts between small-scale and industrial fisheries (DuBois & Zografos, 2012).

Understanding the degree to which industrial-scale fisheries are operating in inshore fishing areas, the most common form of illegal fishing in the region (Doumbouya et al., 2017), is important to inform the existence and extent of the interactions, if any, between large-scale and small-scale fisheries, and to develop a strategy to meet social, environmental, economic and policy objectives of countries extensively relying on fish for their populations. However, there is a concern over the lack of industrial fisheries effort data, spatial distribution and fleet mobility within the EEZs of African countries. The cause of this data deficiency depends on the operational structure and behaviour of fisheries (Belhabib et al., 2012). For instance, large-scale foreign industrial vessels often do not land catches in West Africa, so catch and effort data sharing with national fishing agencies is often challenging, if at all possible without proper measures (Belhabib et al., 2016).

Spatial data of fishing effort are often collected through limited at-sea observer programmes and Vessel Monitoring System (VMS). The availability of VMS data is severely restricted; the data are usually aggregated at the monitoring station ashore, limiting its availability for users (Abdul Sherif, 2014; Deng et al., 2005) as they are typically only available (with exceptions) to governments. Hence, recent applications of automatic identification system (AIS) data in studying fisheries have emerged to offer an alternative to estimating spatially-explicit fishing effort in data poor fisheries. AIS was developed for vessel collision avoidance, and the system shows the flag state while detecting its geographical locations at high spatial resolution (McCauley et al., 2016). Recently, the system has been used to build a global database of large-scale fishing operations, covering the majority of the fishing vessels larger than 24 m in length (Kroodsma et al., 2018). Fishing effort predicted through AIS data that are made available publicly offer new opportunities to study fishing activities in areas where traditional monitoring systems are largely lacking or inefficient (Arias & Pressey, 2016). AIS functioning depends on the willingness of vessel operators, or the legislative framework within which they operate. In some cases, the geographic representation of AIS fishing effort estimates was questioned (Amoroso, Parma, Pitcher, McConnaughey, & Jennings, 2018). It comes as no surprise that when AISs are shut down, vessels and hence their activities (fishing effort) are equated to zero, which biases fishing effort estimates. However, given the lack of present alternatives, AIS has been used to study the extent of the fishing effort, if at all, in a conservative manner.

In African coastal waters, it is critical to understand the extent of this form of illegal fishing and the spatial overlap between small and large-scale fisheries, as it highlights the potential implications for African countries' marine policy objectives such as marine safety (FAO, 2010), the protection of small-scale fishers' livelihood, and further contribute to the advancement of internationally-agreed objectives/principles, including the Small-Scale Fisheries Guidelines produced by the United Nations Food and Agricultural Organization (Basurto, Franz, Mills, Virdin, & Westlund, 2017).

In this paper, we assess the spatial distribution of industrial fishing fleets within African coastal waters by using AIS data-estimated fishing effort and evaluating the potential extent of industrial fishing fleets' operations in inshore areas, where most small-scale fishing activities take place. We used the AIS data-predicted fishing effort provided by Global Fishing Watch (GFW), a non-profit research platform which uses a convolutional neural network, a form of machine learning, to predict when vessels are engaged in fishing activity based on

TABLE 1 Identified inshore fishing areas in Africa

EEZ	Prohibition zone (nautical miles from shore) [km]	Table	Reference[a]	Degree of exclusion
Angola	4–12 [7.4–22.2]	The legislation sets various boundaries per gear type, sector, and flag Foreign industrial fishing within the 12 nautical miles zone is prohibited. Artisanal boats operate from shore to 4 nautical miles, semi-industrial domestic boats beyond 6 nautical miles, domestic pelagic purse-seines and deep sea boats beyond 8 nautical miles	Ministerio Das Pescas, (2003), Pramod, Pitcher, Pearce, and Agnew (2008)	Complete[b]
Benin	5 [9.3]	Area reserved for artisanal fisheries (http://statpeche-uemoa.org/index.php/Benin)	FAO (2017c)	Complete
Cameroon	3 [5.6]	Industrial fishing prohibited within 3 miles, reserved for artisanal fishing	Lembe (2014, IUCN (2015)	Complete
Cape Verde	3–12 [5.6–22.2]	The region within 3 nautical miles is exclusively reserved for the artisanal and domestic industrial fishing activities and the prohibition of the foreign fleet fishing activity within 12 nautical miles. We assign full prohibition for Cape Verde Domestic fleet at 3 nm, and for the foreign fleet at 12 nm	ICCAT (2009)	Complete
Congo	6 [11.1]	Zone reserved for artisanal fisheries	Republique du Congo (2014), IUCN (2015)	Complete
Congo, DRC	0	No mention of a prohibition of access to a given zone by industrial vessels	Republique Democratique Du Congo (2009, IUCN (2015)	None
Côte d'Ivoire	3 [5.6]	Zone reserved for artisanal fishing	Diaw and Haakonsen (1992), Failler, Al Ayoubi, and Konan, (2014)	Complete
Djibouti	0	No restrictions in place for domestic fishing vessels, however, no trawling or foreign fishing is allowed within Djibouti's waters (http://www.fao.org/3/a-br791e.pdf). Given that Dibouti's fleet is artisanal, we label all of Djibouti's EEZ as a zone under complete prohibition	Cofrepeche (2013)	Complete
Equatorial Guinea	4 [7.4]	Prohibition of all industrial fishing gear in the zone reserved for artisanal fisheries	Republica de Guinea Ecuatorial (2003)	Complete
Eritrea	6.5 [12]	Applicable to trawlers only	FAO (2017a)	Partial
Gabon	3–6 [5.6–22.2]	The 3 nautical miles zone is reserved for artisanal fisheries, 3–6 domestic industrial fishing is allowed, and beyond 6 nautical miles, all forms of fishing (foreign fishing not allowed under this zone; Also see http://www.fao.org/fi/oldsite/FCP/fr/GAB/body.htm [Accessed on 4/26/2018])	Republique du Gabon (1994)	Complete
Ghana	12 [22.2]	In Ghana industrial and inshore vessels are not permitted to operate within 12 nautical miles of the shoreline	Benkenstein (2016)	Complete
Guinea	12 [22.2]	The national authorities have demarcated a zone of 10 sea miles along the coast exclusively for small-scale maritime fisheries	FAO (2002a)	Complete
Guinea-Bissau	12 [22.2]	Zone reserved for artisanal fisheries	Doumbouya et al. (2017)	Complete
Kenya	5 [9.3]	commercial trawling within five nautical miles of the coast is prohibited	Lestang (2007)	Partial
Liberia	6 [11.1]	An Inshore Exclusion Zone (IEZ) reserves the six nautical miles closest to shore for the sole use of subsistence, artisanal and semi-industrial fishing activities. Consequently, trawling of any type by industrial and commercial fishing activities is not allowed inside the IEZ. "semi-industrial fishing" means small-scale commercial fishing using a semi-industrial fishing vessel	Abdul Sherif (2014), Liberia Ministry of Agriculture (2010, 2010)	Complete

(Continues)

TABLE 1 (Continued)

EEZ	Prohibition zone (nautical miles from shore) [km]	Table	Reference[a]	Degree of exclusion
Madagascar	12 [22.2]	Long-line and semi-industrial fisheries are undertaken in zones between 12 and 20 nautical miles around Reunion Island and Madagascar	Le Corre et al. (2012)	Partial
Mauritania	6 [11.1]	Zone reserved for artisanal fisheries	Boulay (2013)	Complete
Mauritius	2 [3.7]	Fishing zones are regulated (two miles in the West coast and eight miles in the East).	FAO (2017b)	Complete
Mayotte	24 [44.4]	Industrial fishing activities are restricted to beyond the 24 nautical miles zone within Mayotte EEZ	Le Corre et al. (2012)	Complete
Morocco	12 [22.2]	Foreign trawlers are not allowed within 12 miles of the coast. Domestic vessels are allowed. Hence we use complete prohibition for foreign, and none for domestic vessels	Baddyr and Guénette (2001)	Partial
Mozambique	3–12 [5.6–22.2]	All industrial trawl fishing is restricted beyond 3 nautical miles from the coastline. Foreign fishing vessels are not allowed to fish in territorial waters (12 nautical miles). We classify these restrictions as full per category	FAO (2002b)	Complete
Namibia	0	None	N/A	None
Nigeria	5 [9.3]	Zone reserved for artisanal fisheries	FAO (2000)	Complete
Sao Tome & Principe	12 [22.2]	Area reserved for artisanal fisheries, all industrial fishing is prohibited except under a special authorization by the government. We consider this a partial prohibition given the lack of information on special authorizations	IUCN (2015)	Partial
Senegal	6 [11.1]	Industrial vessels are prohibited from fishing at least within the 6 nautical miles zone (http://www.fao.org/docrep/V9982E/v9982e3n.htm)		Complete
Sierra Leone	6 [11.1]	Zone reserved for artisanal fisheries (http://www.spcsrp.org/en/sierra-leone-0)	INTERPOL (2014)	Complete
Somalia	24 [44.4]	The protection zone that protects coastal artisanal fishers and in which fishing vessels are not permitted to enter is up to 24 nautical miles. Only coastal artisanal fishers are allowed to fish within 24 nautical miles	Ministry of Fisheries and Marines Resources (2016)	Complete
South Africa	0	Fisheries are regulated by quota and species within various zones	ANON (2003)	None
Tanzania	12 [22.2]	Foreign, including EU vessels to fish beyond 12 miles zone (i.e. complete for foreign vessels; http://www.fao.org/docrep/V9982E/v9982e41.htm). There are no known restrictions on the rest of the domestic fleet	European Commission (2005)	Complete
The Gambia	7 [13]	No industrial fishing vessel is allowed to fish within the seven-nautical mile limit which is exploited by artisanal fishermen (http://www.fao.org/fi/oldsite/FCP/en/gmb/body.htm)	INTERPOL (2014)	Complete
Togo	8 [14.8]	Zone reserved for artisanal fisheries (http://www.fao.org/fi/oldsite/FCP/fr/TGO/profile.htm)		Complete
Western Sahara	12 [22.2]	Foreign trawlers are not allowed within 12 miles of the coast	Baddyr and Guénette (2001)	Partial

Notes: Inshore fishing areas include designed areas that limit industrial-scale fishing: complete prohibition refers to the prohibition of all types, gears, and flags of industrial fishing; partial prohibition refers to prohibitions applying only on certain types, gears and/or flags of industrial fishing vessels, and no prohibition refers to the absence of evidence that a protected/restricted/or prohibited area exists.

[a]Additional interviews were conducted with local experts and government representatives from Mauritania, Senegal, Guinea-Bissau, Sierra Leone, Liberia, Ghana, Madagascar, Somalia, and South Africa to further clarify outstanding issues, and corrected for accuracy, such as the case of Guinea.

[b]A complete prohibition applies in various cases: (a) when the prohibition is directed to foreign fishing and no domestic industrial fishing was undertaken during the time of the analysis, (b) when prohibitions apply at various degrees in separate areas, for example, semi-industrial fishing is allowed between 3 and 6 nm but completely prohibited under 3 nm from the coast, and (c) when no industrial fishing is allowed in one homogeneous area. The analysis takes into account flags of vessels to reflect (a) and various prohibition areas to reflect (b).

their movements (Kroodsma et al., 2018). We reviewed the legal definition of inshore zones as a proxy for where small-scale fishers are operating, and then calculated the hours of industrial-scale fishing in these inshore areas and relative contribution of different flag states.

2 | MATERIALS AND METHODS

2.1 | Review of existing inshore fishing areas in African coastal states

This study includes 33 African maritime countries (and territories) bordering the Atlantic and Indian Oceans (excluding the Mediterranean), with their Exclusive Economic Zones (EEZ) totalling an estimated marine area of 10.3 million km^2. Approximately, 11% of the area is continental shelf.

An inshore fishing area is defined here as the distance from shore where artisanal fishing activities mostly take place. In many African maritime countries, inshore fishing areas correspond to coastal waters that are formally designated to limit or exclude industrial-scale fishing. Therefore, we performed a review of maritime regulations recorded in the FAO regulations database (www.fao.org/faolex/country-profiles/en/) and other relevant literature described in Table 1 to identify any designated inshore fishing areas in the study area. We used keywords: "artisanal fishing zones," "coastal fishing zones," "inshore exclusion area," "prohibited area," "inshore exclusion zone," and "Fishery Excluded Area" in the search. As noted earlier, we used those legally defined marine areas as proxy for the area where small-scale fishing vessels operate though their area of activities may exceed those designated marine zones (Belhabib, Koutob, Sall, Lam, & Pauly, 2014).

2.2 | Predictions of fishing locations and duration

Using the dataset described in Kroodsma et al. (2018), we predicted fishing locations and calculated the distance of these locations from the nearest point on the coastline based on AIS data for the period 2012 to 2016. In this AIS fishing tracks dataset, fishing intensity is measured as the number of hours spent fishing at each location. We calculated the fishing intensity, for each year from 2012 to 2016 that was predicted within the EEZ boundary and within inshore fishing areas (Table 1).

2.3 | Small-scale fishing areas in African coast: using legally designated coastal marine areas as a proxy

We have found in the literature, and after consultation with local and national organizations in Africa, legally designated marine areas for small-scale fisheries in 29 out of the 33 African countries we reviewed information for this study. The width of these prohibited or restricted marine areas ranges from 2 to 24 nautical miles from the shoreline (Figure 1). Some areas were subject to various restrictions such as foreign fishing prohibition in areas under the 12 nautical marks in Angola, while domestic vessels could operate between 4 nautical miles and beyond, in Mozambique and Cape Verde ranging between 3 and 12 nautical miles. There was no documentation of a legally designated inshore fishing area in the Democratic Republic of the Congo, Djibouti, South Africa and Namibia that restricts industrial fleets.

Given the variety of area restriction/prohibition, we profiled two main types of restrictions–with Djibouti, Namibia, South Africa and the Democratic Republic of the Congo having designated none—(see Table 1).

2.4 | Inshore marine Area designated exclusively to small-scale fisheries (all industrial fishing is prohibited)

All forms of industrial fishing by all gears within these waters are prohibited, and hence all forms of fishing activities by industrial domestic or foreign industrial fleets are restricted to the area beyond the limits set by the prohibition zone, any industrial fishing vessels fishing within these areas would be sanctioned under national laws, which aim at protecting small-scale fishing activities, in terms of livelihoods, fish stocks and safety at sea. This applies to Angola, Benin, Cameroon, Cape Verde, Congo, Côte d'Ivoire, Equatorial Guinea, Gabon, Ghana (excluding tuna vessels which operate further), Guinea, Guinea-Bissau, Liberia, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Nigeria, Senegal, Sierra Leone, Somalia, Tanzania, The Gambia, and Togo.

In Cape Verde, the legislation reserves the area within three nautical miles from shore to artisanal fisheries, and the area within 3–12 nautical miles to industrial domestic (domestically flagged vessels) fisheries, while foreign fishing is completely prohibited within 12 nautical miles from shore (ICCAT, 2009). Similar regulations apply in Gabon with the area between 3 and 6 nautical miles is reserved for Gabonese flagged industrial vessels, the area between 0 and 3 nautical miles reserved for Gabonese artisanal fisheries, and hence all foreign fishing operations between 0 and 6 nautical miles are prohibited under the current legislation (Lembe, 2014). These cases also apply to Mozambique and Angola (Table 1, Figure 1). In these cases, we allocated "partial prohibition" to the larger area. For example, in Angola where all foreign fishing activity is restricted beyond the 12 nm mark, we considered all foreign fishing under the 12 nm mark as prohibited, although we indicate it in Figure 2 as being partial, this only implies that, for example, domestic semi-industrial vessels could operate within the 4–12 nautical miles. These are however unlikely to be detected as they do not typically carry AIS onboard.

2.5 | Inshore marine areas of partial restriction for large-scale fisheries

We found nine countries that have set legal restrictions in their inshore areas, either related to selected gear use or origin, size and

provenance of the fishing vessels, and/or the agreements under which they operate. In these areas, partial prohibitions are in place for some forms of industrial fishing, or industrial fleets under a given agreement. Such is the case in Eritrea (EEZ surface: 78,383 km^2) where trawling is prohibited within the 6.5 nautical miles, in Kenya (EEZ surface: 162,794 km^2) within the five nautical miles. Trawling by foreign fleets is prohibited Western Sahara (EEZ surface: 300,942 km^2) within the 12 nautical miles from shore and where legislation is in place to regulate minimum allowable trawling distance, with no further restrictions implemented on other industrial gear types (Fennessy, 2004). Similar restrictions apply for long liners operating in Madagascar (EEZ surface: 1,200,330 km^2). Another example applies for Sao Tome and Principe (EEZ surface: 165,345 km^2) where all industrial fishing is prohibited within 12 nautical miles of the coast, except with special permission from the government (IUCN, 2015). Note that the lack of literature and online documentation on the existence of prohibited zones in some countries does not imply that these zones are absent or that restrictions do not apply. It does not appear that the surface area of the EEZs is a determinant factor for the presence or absence of protections around inshore areas. The latter may be the result of more complex processes and could be motivated by the existence and/or the extent of an existing artisanal sector, governance processes, safety at sea and other conservation targets.

2.6 | Calculating predicted fishing hours in inshore areas by large-scale fishing fleet

The Global Fishing Watch system allows us to extract information on the location of fishing vessels, their predicted fishing operations and track, and their identification. Vessel gear type and size are obtained by matching the name, call sign and IMO number broadcast by a vessel with official registries or by using the results of Global Fishing Watch's convolutional neural network for vessel classification (Kroodsma et al., 2018). Vessel flags are determined by the combination of the MMSI number they broadcast (the first three digits are supposed to correspond to flag state) and an extensive review by Global Fishing Watch. The programme detects fishing patterns using a convolutional neural network, and hence measures those fishing patterns against time and provides the predicted number of fishing hours depending on the tracks of the fishing vessel. We extracted the total number of fishing hours from African EEZs by flag, that is, recorded the number of fishing hours whenever the fishing operation overlapped with the EEZs of countries. Whenever the distance of the fishing operation from the coast is within the area of prohibition/restriction (Table 1), the number of fishing hours was recorded separately for each flag state, and by Exclusive Economic Zone. Using the total number of fishing hours and vessel capacity (engine power), we calculated

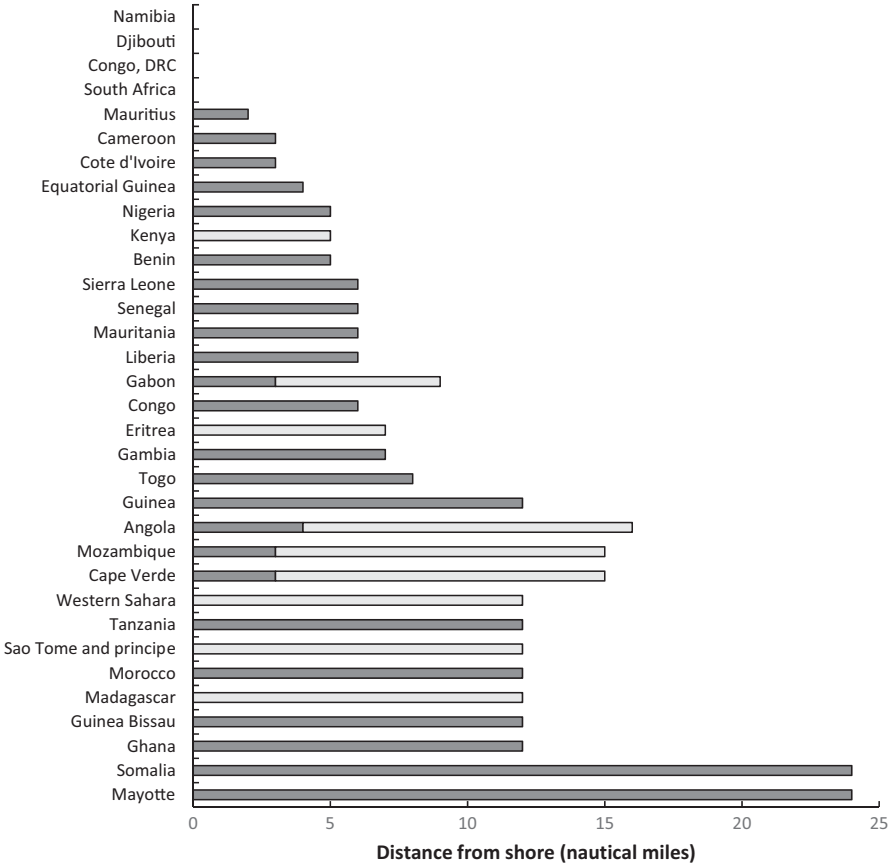

FIGURE 1 Inshore fishing areas in Africa. The area is measured as the distance from the shoreline in nautical miles. Light grey indicates areas of partial prohibition (restrictions on some gears types, sectors, or on foreign fishing), and dark grey indicates areas of complete prohibition (no industrial fishing activity is allowed)

the number of kWhours (this is calculated as the product of the number of hours and vessel's engine power) representing the fishing intensity by vessel flag, and by Exclusive Economic Zone, which allows to understand the fishing effort within inshore areas. We use kWhours as a measure of effort because even though the number of hours can be similar from a vessel to another, the capacity of the vessel (e.g., engine power) is a good indicator of the footprint of the fishing vessel; typically higher capacity vessels will have a higher footprint.

3 | RESULTS

3.1 | Large-scale fishing activities in the EEZs of Africa

The Global Fishing Watch programme identified a total of 4.2 million hours of fishing within the African EEZs between 1 January 2012 and 31 December 2016, corresponding to 836,525 hr per year. This is equivalent to a total energy of 4.9 billion kWhours of fishing effort spent within African EEZs by industrial vessels or around 970 million kWhours per year. We estimated the annual average of 23.5 million kWhours/year (27,000 hr/year) inshore of the six nautical miles (11.1 km) zone, which is the average delimited zones across all countries reserved for small-scale fishing activities, and 369 million kWhours/year (277,700 hr/year) of predicted fishing effort in the marine area that is within 30 nautical miles (56 km) from the shore. We also estimated 200 million kWhours/year of fishing effort (130,600 hr/year) between 30 and 40 nautical miles (56–74.1 km) (Figure 2a, b). The fishing effort then decreases to 25.7 million kWhours/year (32,000 hr/year) between 80 and 90 nautical miles from the coast, and further declines outside EEZ boundaries beyond 200 nautical miles (370.4 km) from the coast (Figure 2). The number of fishing hours shown in Figure 2 supports the observation that African large-scale fisheries generally occur within the 25–50 nautical miles zone (Belhabib, Greer, & Pauly, 2017; Stewart et al., 2010; Watson, Kitchingman, Gelchu, & Pauly, 2004). Analysis between matched (RM) and unmatched (NN) vessels illustrates similar patterns in terms of concentration of fishing effort around coastal areas, with however a lower number of hours for vessels that have not been matched to a registry (Figure S2).

3.2 | Estimated fishing effort of large-scale fisheries in inshore fishing areas

The total number of individual or unique large-scale fishing vessels operating in the 33 African EEZs and territories researched bordering the Atlantic and Indian Oceans (excluding the Mediterranean) was 1,398 unique vessels during the 2012–2016 time period, of which 73% were matched to a fishing vessel registry, and 27% could not be matched to a registry, but were defined as fishing vessels through a neural network analysis. The number of unique vessels covered (regardless of the number of EEZs they appeared in) increased from 308 unique vessels, of which 88% were matched to a registry, to 1,017 vessels in 2016 (regardless of the number of EEZs they appeared in) of which 70% were matched to a registry. This illustrates how coverage increased since 2012. While this may present a potential bias in the temporal evolution of the fishing effort, which is not the focus of this study, it implies that the analysis is conservative in that it may not account for a number of vessels in earlier years. Of the total number of vessels, 582 vessels operated in inshore areas at least once within 1 to 5 different Exclusive Economic Zones. Vessels detected were of various nationalities, notably: South Africa (16% of the total number of vessels), Spain (15%), Taiwan (12%), China (8%).

Overall, we estimated a total fishing effort of 4.9 billion kWhours fished within the EEZs of the African nations under study, corresponding to 4.2 million hours (Table 2), 75% of which were by vessels matched to fishing vessel registries. Although South Africa comes first in terms of the overall fishing time spent by all fleets within its EEZ, that is, nearly 17% of the fishing time (511,000 hr) and 10% of the fishing effort (421 million kWhours), Western Saharan EEZ comes first in terms of fishing effort by all fleets fishing therein with 875 million kWhours (18% of the total fishing effort), indicating that higher capacity vessels operate therein, and 8% of the fishing time. This denotes of major variation in vessel capacity between EEZs (Figure 3). Around 9% of the fishing time by all fleets (347,000 hr) is spent in Madagascar, where restrictions are partial, which is equivalent to 5% of the fishing effort (Figure 3).

The fishing effort in both fully and partially restricted areas is 3% (166 million kWhours) of all detected fishing effort by large-scale vessels in Africa, which corresponds to 180,855 hr and 3.9% of the total time spent fishing. Fishing effort in areas of full prohibition, typically regarded as illegal fishing, represented as 5.9% of all fishing effort within the EEZs of the corresponding countries, and 3% in areas of partial prohibition (Table 2). Considering this measure of the fishing effort as an appropriate reflection of the fisheries footprint of the large-scale fleet in West Africa and that these vessels infringe upon national legislations, fishing vessels potentially spent at least 81 million kWhours fishing illegally in artisanal and inshore zones. We note that there exists an uncertainty linked to the fact that nearly 25% of all the likely fishing vessels were identified through a neural network classifier instead of by matching the vessels to official registries and that AIS signals are shut down at will (Figure S1). Table 2 illustrates some differences in the number of hours and the percentage of effort spent in restricted areas (full or partial prohibition). For example, vessels matched to the registry spent 3.85 of their fishing time in restricted areas subject to complete prohibition, in comparison with vessels that were not matched to a registry, which appear to have spent over 15% of their fishing time within restricted areas subject to a complete prohibition. However, this pattern is not mirrored in areas of partial prohibition where the percentage of fishing within inshore waters seems is not significantly different between NN vessels and RM vessels. This implies that these differences may not be due to the higher uncertainty associated with neural network detected vessels but other factors such as the location of the vessel, the type of the area, the fishing gear, etc. which are not covered by this analysis.

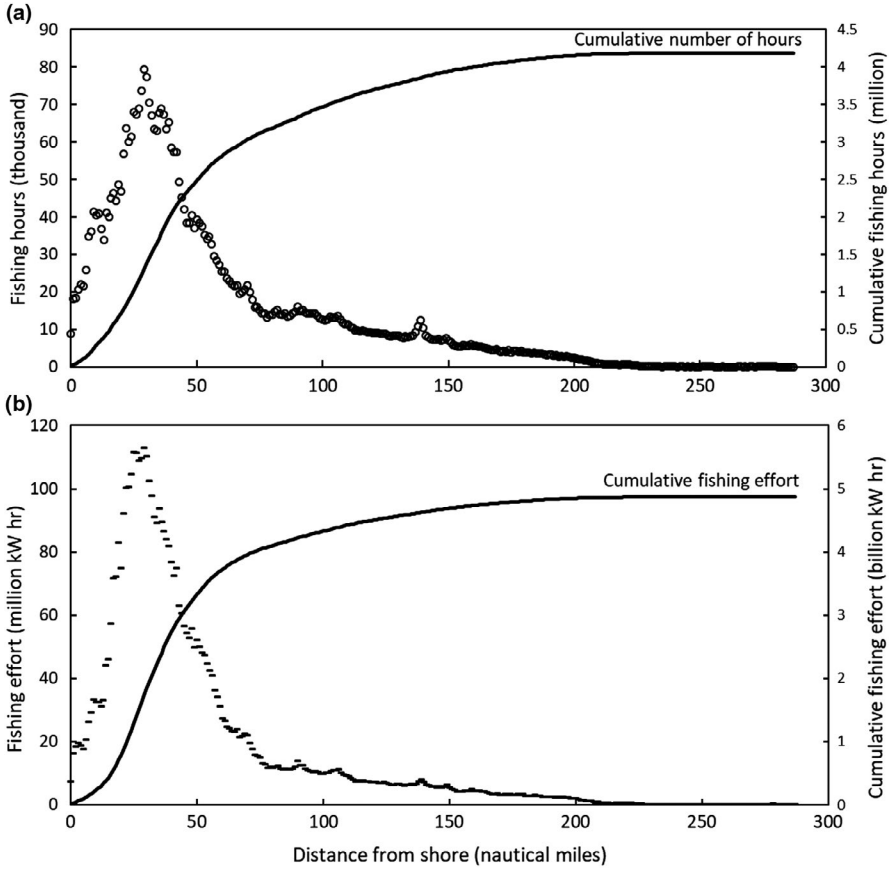

FIGURE 2 (a) Duration (in hours) of AIS detected fishing activities of industrial fishing vessels, and (b) corresponding fishing effort in kWhours by distance from shore within African waters with the cumulative estimates in the line plots

TABLE 2 Fishing hours in inshore fishing areas in the Exclusive Economic Zones (EEZs) studied here from 2012 to 2016

Area profile	Total (hr)	Number of hours for matched (RM) versus unmatched (NN) vessels	Within inshore fishing areas (hr)	Hours within restricted zones for matched (RM) and unmatched (NN) vessels	Percentage of fishing within inshore waters	Percentage of fishing within inshore waters for matched (RM) and unmatched (NN) vessels
Fishing in EEZ where inshore areas are subject to a complete prohibition	2,287,248	NN[a]: 414,020 RM[b]: 1,873,228	135,223	NN: 63,526 RM: 71,697	5.9	NN: 15.3% RM: 3.8%
Fishing in EEZ where inshore areas are subject to a partial prohibition	935,705	NN: 220,782 RM: 714,923	31,330	NN: 4,497 RM: 26,833	3.3	NN: 2.0% RM: 3.8%
Fishing in EEZ where inshore areas are subject to no prohibition[c]	1,024,058	NN: 433,728 RM: 590,331	No documented area for artisanal fisheries			
Total	4,247,012	NN: 1,068,530 RM: 3,178,482	166,553	NN: 68,023 RM: 98,530	3.9	NN: 6.4% RM: 3.1%

[a]Neural Network estimate when vessel identifiers could not be matched with existing registries. This represents the source of uncertainty in fishing data, along with false positives related to vessels visiting ports.

[b]Vessel matched with Fishing Vessel Registries.

[c]We theoretically set a limited zone of six nautical miles for these EEZs (the overall average of limitations) and found that 1,080 hr were fished within that distance from shore (<1%).

During the study period, from 2012 to 2016, African flagged vessels have had the highest fishing effort within inshore fishing areas, that is 72 million kWhours, which constitutes 6% of the total fishing effort in kWhours by the same fleet within the EEZs of Africa. African flagged vessels were responsible for 43% of the total number of estimated hours fished within inshore areas by all large-scale fishing fleets. Indeed, African flagged vessels rank first in terms of both fishing effort and total number of hours spent fishing in inshore waters (Figure 4). Ghanaian flagged vessels, for example, were identified to spend the highest number of estimated fishing hours (equivalent of 38 million kWhours), constituting nearly a quarter (23%) of fishing by all large-scale fishing fleets within restricted areas. Most of this Ghanaian fishing effort within restricted areas (>83%) occurs within the Ghanaian inshore area that is restricted for trawling. Among non-African flagged vessels operating in African restricted coastal waters, South Korean flagged vessels spent an estimated 42 million kWhours fishing within restricted areas, that is, 26% of all South Korean fishing effort in Africa are spent within restricted areas. South Korean fishing effort within restricted areas constituted a quarter (25%) of the total fishing effort by all fleets within restricted areas (Figure 4), ranking South Korean flagged vessels second after African flagged vessels in terms of fishing within inshore areas. European Union flagged vessel was identified to spend nearly 20 million kWhours fishing in African restricted fishing areas, or about 2% of their total fishing effort. EU flagged vessels' fishing effort within restricted areas constituted 12% of the total fishing effort within restricted zones by all fleets, ranking EU flagged vessels third in terms of fishing within the restricted areas of Africa. The majority of the estimated fishing effort by the European flagged vessels in small-scale fishing areas were by Greek vessels (62% of the total fishing effort by EU flagged vessels within restricted areas), followed by Spanish vessels (22%), and French vessels (12%), with smaller contributions by Portuguese, Italian, and other EU flagged vessels. Chinese flagged vessels spent an estimated 8 million kWhours fishing in restricted areas that are reserved for small-scale fishing, which equates 2% of their total fishing time, and 5% of the total time spent in restricted zones by all fleets together, ranking Chinese fleets 4th after African flagged vessels, Korean flagged vessels, and EU flagged vessels. The contribution of each fleet to the total fishing effort spent in restricted area may be biased by the fact that vessels switch off their AIS signals. Indeed, maps illustrating a point in time when vessels AIS signal was lost or switched off, illustrates that the above results are a conservative estimate of the fishing effort, and while the fishing effort could increase if these vessels were accounted for, the trend in contribution of individual fleets would remain unchanged (Figure S1).

Despite the overall low percentage (5.9%) of fishing in inshore areas with a complete prohibition, and 3.3% in areas of partial restriction (Table 2), industrial fleets spent a significant time in prohibited inshore areas per EEZ.

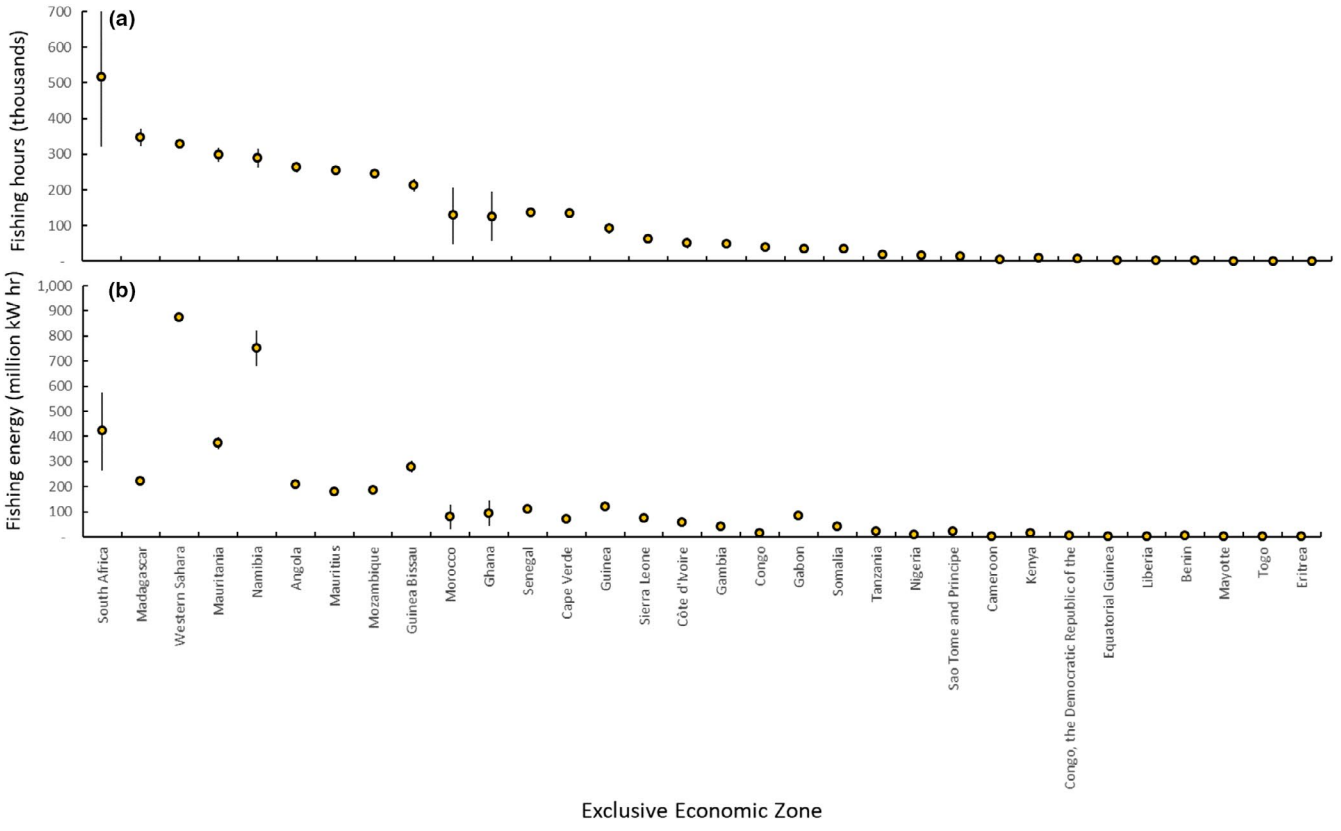

FIGURE 3 Number of hours fished (a), and fishing effort (b) by the industrial fleet per EEZ by vessels broadcasting AIS, 2012–2016, showing levels of uncertainty related to the algorithm associating tracks to fishing activity [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Flag contribution to the total effort and areas of high vulnerability

We estimated that, in Somalia, where all forms of industrial fishing are prohibited within the 24 nm zone, a staggering 93% of large-scale fishing activities occur within areas reserved for artisanal fishing, all of which is operated by South Korean flagged industrial vessels, which rank second in terms of fishing within the inshore areas of Africa. Fishing by South Korean flagged vessels within the inshore waters of Somalia, that is, those reserved for the artisanal fleet, accounts for nearly 20% of the total effort spent within inshore areas of Africa by all fleets. In Eritrea and Equatorial Guinea, which rank relatively low in terms of total fishing time within inshore waters (1% of the total time by all fleets operating within African waters), industrial fleets spent over 38% and 33% of all industrial fishing operations in the inshore areas strictly or partially reserved for small-scale fisheries, respectively. Large-scale fleets spent 28% of their fishing time within inshore areas of Ghana, where trawling is banned. Nearly 95% of that effort spent within the inshore waters of Ghana are fished by Ghanaian flagged fleets. It is unclear, however, the level and origin of the beneficial ownership of these fleets (Samari, 2019). This means that vessels in these countries spend a large portion of their time fishing in restricted zones, which would typically be described as illegal (Figure 5).

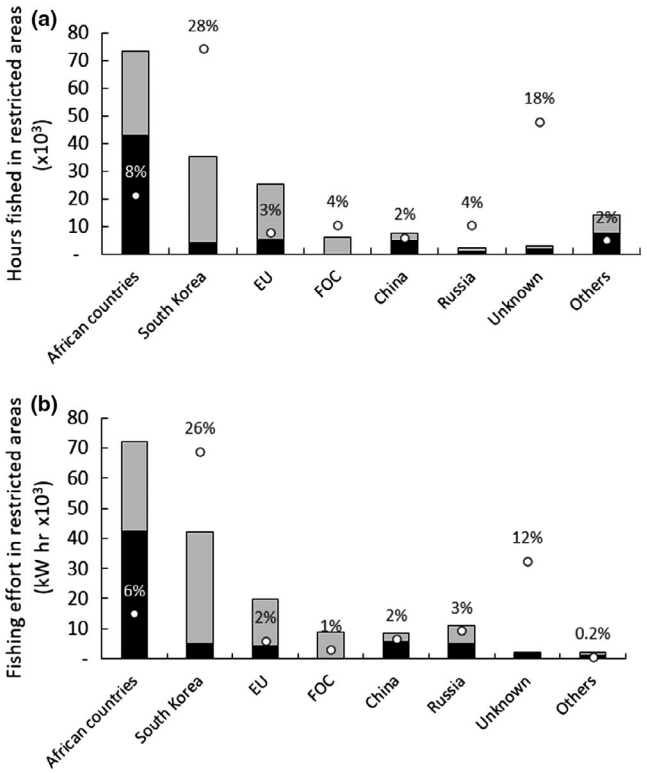

FIGURE 4 Number of hours (a) and kWhours (b) fished in inshore areas of complete and partial prohibition (bars) and percentage (circles) of hours spent fishing in these inshore areas over the total number of hours of each fishing fleet. Hours fished by vessels matched against fishing vessel registries are shown in black bars, and hours fished by vessels which were deemed fishing using the neural network are shown in grey

4 | DISCUSSIONS

The results from this study suggest that large-scale fishing vessels that carried active AIS technology commonly fished in nearshore waters (within 50 nautical miles from the coast) in Africa, and these fishing operations within inshore fishing areas were mostly undertaken by vessels from a limited number of flag countries, namely South Korea, EU countries (Greece, Spain), flag of convenience fleets and China, in descending order of fishing hours, and mainly occurred in a restricted number of EEZs, notably within the states which can be described as vulnerable for their lack of capacity to enforce fisheries regulations (Doumbouya et al., 2017). Examples of these countries include Somalia, Eritrea and Equatorial Guinea where fishing in restricted areas constitutes 93% and 46%, and 38% of all large-scale fishing, respectively.

In West Africa, fishing within inshore prohibited or restricted areas represents over 60% of all caught and sanctioned fishing infractions (Doumbouya et al., 2017). The argument here does not lay within the illegality of these fishing operations only, but within the idea that the creation of inshore fishing areas limited whether fully or partially to small-scale fisheries, is commonly one of protection of fish stocks (juvenile fish), reduce the competition with small-scale operators or ensure the safety of small-scale fishing operations. Coastal and estuarine waters constitute important reproductive grounds and nurseries for many fish species (Sheaves, Baker, Nagelkerken, & Connolly, 2015; Vasconcelos et al., 2010). Some of these habitats constitute a shelter where species display higher tolerance to environmental change (Vasconcelos et al., 2010). Hence, the closure of coastal waters to, for example, industrial fishing, which commonly has a higher footprint on fish stocks (Belhabib, Sumaila, & Pauly, 2015) is of key importance for conservation. Indeed, studies have shown that the distribution of essential nursery habitat is key in understanding and predicting the potential production of adult fish (Sundblad, Bergström, Sandström, & Eklöv, 2014). In addition, habitat protection is key for conservation, particularly where available coastal habitat is scarce (Sundblad et al., 2014). Beyond the environmental sustainability issue, the co-occurrence of small-scale and large-scale fishing activities poses risk to maritime safety. For example, in the sub-region of West Africa, inshore fishing activities by large-scale vessels have resulted in collisions with pirogues, leading to over 250 deaths of artisanal fishers, annually (Belhabib, 2017). Anecdotally, it is accounted by local fishers that the death toll can be much higher in other regions notably in the Gulf of Guinea, where anecdotal evidence suggests that deaths and disappearances at sea are often not reported by authorities (Belhabib, 2017). Ultimately, regardless of the amount of time spent by the large-scale fleet fishing (illegally) in artisanal zones, the very presence of these vessels, even at a rate of 2% of their total time, such as in the case of Senegal, can result in collisions between industrial fishing vessels and small-scale fishing pirogues leading to 100 deaths at sea (Belhabib, 2017). This further suggests an urgent need to comprehensively consider safety of fishing operations for small-scale fisheries that includes management of both large-and small-scale fishing activities (Petursdottir

& Hannibalsson, 2001). Hence, the effective protection of these coastal zones becomes a matter of urgency for the communities that benefit from them.

A high risk of large-scale fishing in inshore waters, or incursions, is associated with countries that have limited capacity or willingness—given complex social interactions—to monitor their waters. In our analysis, Somalia, Equatorial Guinea, Eritrea and Ghana, where vessels spend a significant amount of their time fishing in prohibited zones, have either a limited capacity to monitor their coastal waters (Somalia, and Eritrea) or have limited willingness because of social interactions such is the case of Ghana where a small sub-sector of the small-scale sector, called Saiko, collects bycatch from vessels (notably Chinese owned trawlers) operating within inshore waters (Belhabib et al., 2016; Nunoo et al., 2014; Penney, Wilson, & Rodwell, 2017). Industrial fishing operations within artisanal inshore zones put a strain on food security (Belhabib et al., 2016), and the maritime safety and security (Glaser, Roberts, Mazurek, Hurlburt, & Kane-Hartnett, 2014) of these countries. Interestingly, Somalia shows high volume of foreign fisheries operated in small-scale area during 2012–2015, but no AIS signals (hence fishing tracks) were detected in 2016. Anecdotal information suggests that this sudden change was caused by the fact that those vessels were hesitant to report their position to other boats, hence revealing themselves to potential pirates within the vicinity, but also because of increased international efforts aimed at monitoring Somali waters against piracy (Belhabib, Sumaila, & Billon, 2019).

Industrial incursions into artisanal zones lead to increased competition with artisanal sectors both the sustainability of fisheries in Africa but also the social and economic wellbeing of coastal communities. Whether in the case of Ghana where the *Saiko* (artisanal fishermen) are outcompeting traditional artisanal fishers (Belhabib et al., 2017; Penney et al., 2017), or in the case of the sardinellas (*Sardinella* spp.) fisheries of West Africa which have been targeted by both industrial and small-scale fisheries within Morocco, Senegal, Mauritania, Gambia, and Guinea-Bissau, causing a sectoral conflict (Belhabib et al., 2014). While sardinella populations in many African EEZs are fully to over-exploited, they remain an important source of food and income for many small-scale fisheries (Belhabib, Sumaila, & Pauly, 2015).

Designating inshore areas, or areas that are reserved for small-scale sectors, is necessary to facilitate the allocation of resources between small-scale and large-scale sectors, with, however, to serve their objective, which is to reserve access to small-scale fisheries, more effort and capacity to implement such prohibition are necessary as the capacity to monitor and detect potential infringement by the large-scale fishing sector is rather low. To this end, we argue that spatial AIS data can be a key to advance the regional ocean governance.

Uncertainties exist in the use of AIS data to estimate the geographical distribution of industrial fishing activities in African coastal water. First, vessels can turn off their AIS during fishing activities and this offline period would lead to an underestimation of the

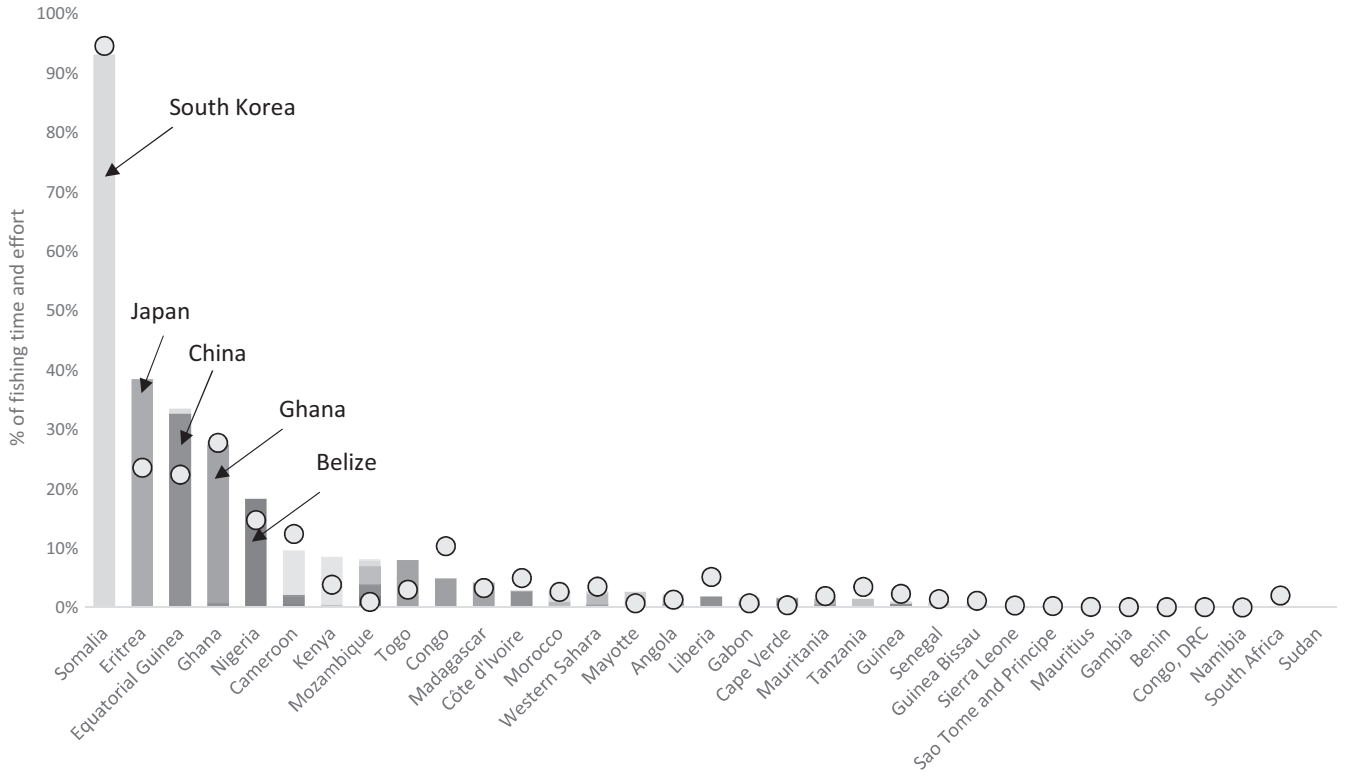

FIGURE 5 Percentage of fishing effort in kWhours (circles) spent fishing in inshore fishing areas relative to their total fishing hours in the African EEZs, and contribution of flag countries to the total fishing effort per EEZ (bars). South Korea's fleet are dominating the incursions in Somalia in terms of relative contribution, Japan in Eritrea, China in Equatorial Guinea, Ghana in its own waters, and Belize in Nigeria

fishing activities, particularly when these vessels are not compliant. This source of uncertainty is not captured herein, but means that the data at hand is conservative as more vessels operate without switching their AIS on (Figure S1). Second, although the algorithm identifying which vessels are fishing has an overall accuracy over 90% (Kroodsma et al., 2018), it does incorrectly label some fishing effort. For this study, the key uncertainty is the number of positions within the restricted areas that are incorrectly labelled as fishing locations, as opposed to false positives associated with vessels visiting ports. However, few vessels land in major African ports, notably in Senegal, Ghana, Côte d'Ivoire and Namibia. In these cases, vessels either land tuna and tuna like species, and do not fish within artisanal and coastal areas, or they spend less than 3 hr within the artisanal zone leading to port, in which case it is not considered as a fishing activity, further reducing this source of uncertainty. Finally, there exists a level of uncertainty associated with the accuracy of the distance to shore metric. Hence, we conducted a sensitivity analysis to measure the change in the fishing effort if the measure of the distance to shore (Distance to nearest coastline datasets can be found here: http://www.pacioos.hawaii.edu/data/search-results/?text=dist2coast) was one nautical mile closer to shore. We find that an error of one nautical mile would reduce the number of fishing hours by 14% and the fishing effort in kWhours by 13%.

There is also some uncertainty over the classification of vessels, which relies on another neural net classifier, although the latter's accuracy in distinguishing fishing vessels versus non-fishing vessels is at 99% (Kroodsma et al., 2018). Herein, we used two methods, one that matches 75% of vessels to a fishing vessel registry, and a complementary method that relies on a neural network to detect fishing behaviour associated typically with fishing vessels (25% of the vessels), which accurately predicts fishing vessels at 99% accuracy. Whenever possible, we captured these sources of uncertainty in the analysis. Third, the largest bias in the dataset is that the fraction of vessels carrying AIS varies by country and region. Overall, AIS is carried by the majority of the world's large fishing vessels (over 24 m), and a decreasing fraction for smaller vessels. Because larger boats fish farther from shore, as one approaches shore the fraction of the total amount of fishing by vessels with AIS decreases.

5 | CONCLUSION

This analysis illustrates possible ways to detect and assess the effort distribution of industrial fishing in African coastal waters including areas that are designated to small-scale fisheries. It demonstrates how data can be extracted from satellite information and used to (a) monitor industrial fishing activities and their geographic distribution, (b) detect issues around collision risk and (c) analyse the emergence of cross-sectorial competition between industrial and small-scale fisheries. In addition, AIS information could be linked to possible incursions of industrial fleets in restricted/prohibited areas strictly designated for small-scale artisanal and subsistence fishers.

We conclude that using AIS, in addition to existing monitoring systems, to detect and locate fishing activities can be key in reducing monitoring costs through focused and targeted surveillance action, reduce risks of accidents at sea, given the level of incursions into areas that are highly frequented by artisanal fishing fleets, and overall, enhance the status of protection of coastal zones. The use of AIS, along with considerations of political and legal contexts, can enable targeted action, through monitoring, and effective mapping and surveillance of industrial activities as it reveals indicative of patterns between fleet behaviour and state's level of coastal governance, and high risk collision/competition area.

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CONFLICT OF INTERESTS

The authors declare no competing interests.

AUTHOR CONTRIBUTIONS

D.B. and D.K. collected the data, D.B., W.W.L.C. developed the study design, D.B. performed the analysis, D.B., W.W.L.C, D.K., V.W.Y.L., P.J.U. and J.V. wrote the manuscript.

DATA AVAILABILITY STATEMENT

All Global Fishing Watch Data is available online. Data that support the findings of this study are available from the corresponding author upon request.

ORCID

Dyhia Belhabib https://orcid.org/0000-0001-7729-1799

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SUPPORTING INFORMATION

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

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