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Contributed Paper

Threats of illegal, unregulated, and unreported fishing to biodiversity and food security in the Republic of the Congo

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Abstract: Illegal, unregulated, and unreported (IUU) fishing poses a major threat to effective management of marine resources, affecting biodiversity and communities dependent on these coastal resources. Spatiotemporal patterns of industrial fisheries in developing countries are often poorly understood, and global efforts to describe spatial patterns of fishing vessel activity are currently based on automatic identification system (AIS) data. However, AIS is often not a legal requirement on fishing vessels, likely resulting in underestimates of the scale and distribution of legal and illegal fishing activity, which could have significant ramifications for targeted enforcement efforts and the management of fisheries resources. To help address this knowledge gap, we analyzed 3 years of vessel monitoring system (VMS) data in partnership with the national fisheries department in the Republic of the Congo to describe the behavior of national and distant-water industrial fleets operating in these waters. We found that the spatial footprint of the industrial fisheries fleet encompassed over one-quarter of the Exclusive Economic Zone. On average, 73% of fishing activity took place on the continental shelf (waters shallower than 200 m). Our findings highlight that VMS is not acting as a deterrent or being effectively used as a proactive management tool. As much as 33% (13% on average) of fishing effort occurred in prohibited areas set aside to protect biodiversity, including artisanal fisheries resources, and the distant-water fleet responsible for as much as 84% of this illegal activity. Given the growth in industrial and distant-water fleets across the region, as well as low levels of management and enforcement, these findings highlight that there is an urgent need for the global community to help strengthen regional and national capacity to analyze national scale data sets if efforts to combat IUU fishing are to be effective.

Keywords: Africa, distant-water fleet, governance, illegal fishing, industrial fisheries, monitoring control and surveillance, policy, vessel monitoring system

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Amenazas de la Pesca Ilegal, No Regulada y No Reportada para la Biodiversidad y la Seguridad Alimentaria en la República del Congo

Resumen: La pesca ilegal, no regulada y no reportada (INN) representa una amenaza importante para el manejo efectivo de los recursos marinos, lo que afecta a la biodiversidad y a las comunidades que dependen de estos recursos costeros. Los patrones espaciotemporales de las pesquerías industriales en los países en desarrollo a menudo están poco comprendidas, y los esfuerzos globales para describir los patrones espaciales de la actividad de los navíos pesqueros actualmente están basados en los datos del sistema automático de identificación (SAI). Sin embargo, el SAI no es siempre un requerimiento legal en los navíos pesqueros, lo que probablemente resulta en valores subestimados de la escala y la distribución de la actividad pesquera legal e ilegal, lo que podría tener ramificaciones significativas para los esfuerzos enfocados de aplicación de la ley y para el manejo de los recursos de las pesquerías. Para ayudar a completar este vacío en el conocimiento, analizamos tres años de datos del sistema de monitoreo de navíos (SMN) en asociación con el departamento nacional de pesquerías de la República del Congo para describir el comportamiento de las flotas industriales nacionales y de altura que operan en estas aguas. Descubrimos que la huella espacial de la flota de pesquerías industriales abarcó más de un cuarto de la Zona Económica Exclusiva. En promedio, el 73% de la actividad pesquera se realizó en el talud continental (aguas con una profundidad menor a 200 m). Nuestros descubrimientos resaltan que el SMN no está actuando como un disuasivo o no se está usando efectivamente como una herramienta proactiva de manejo. Un máximo del 33% (13% en promedio) de los esfuerzos de pesca ocurrieron en áreas prohibidas apartadas para proteger a la biodiversidad, incluyendo los recursos para la pesca artesanal, con el 84% de la responsabilidad de esta actividad ilegal cayendo sobre las flotas de altura. Dado el crecimiento de flotas industriales y de altura en la región, así como los bajos niveles de manejo y aplicación de la ley, estos resultados resaltan la necesidad urgente que existe para que la comunidad global ayude a fortalecer la capacidad regional y nacional para analizar los conjuntos de datos de escala nacional si se espera que los esfuerzos para combatir la pesca INN sean efectivos.

Palabras Clave: África, flota de altura, gestión, monitoreo del control y la vigilancia, pesca ilegal, pesquería industrial, política, sistema de monitoreo de navíos

Introduction

Globally, industrial fisheries have expanded their fishing grounds and effort to meet the demands of increasing populations (Berkes et al. 2006), leading to approximately 34% of the world's fishing stocks considered overexploited or depleted (FAO 2020). However, harvest rates are 3 times higher and fish abundance 50% lower in regions with less-developed fisheries management compared with intensively managed areas (Hilborn et al. 2020). Undermining efforts to address historical overfishing and manage recovery of these stocks is illegal, unreported, and unregulated (IUU) fishing (Daniels et al. 2016), a broad term that typically refers to industrial fishing activity that does not adhere to national, regional, and international fisheries regulations (FAO 2001). These activities should be differentiated from those of small-scale fisheries, which often fall under different reporting regimes or regulatory frameworks (Song et al. 2020).

Illegal, unreported, and unregulated fishing is estimated to account for 7–17% of the total global catch (FAO 2016). Although occurring in virtually every ocean from high seas to exclusive economic zones (EEZs), IUU fishing is more prevalent in countries with weak governance, meaning developing countries are often disproportionately affected (Petrossian et al. 2015). Many countries in West and Central Africa lack the financial and logistical resources to effectively police their waters and so are increasingly targeted by illegal fishing fleets (Doumbouya et al. 2017). This, coupled with fleet overcapacity, inadequate fisheries regulations, corruption, and a lack of multinational cooperation facilitating vessel movement between jurisdictions, means illegal fishing in West Africa is estimated to account for an additional 40–65% of the reported (legal) catch (Agnew et al. 2009; Doumbouya et al. 2017). Countries, such as Sierra Leone and Ghana, sustain estimated costs of over US$50 million per year (Okafor-Yarwood et al. 2020).

Tackling IUU fishing is, therefore, a top priority to protect marine biodiversity and ensure the sustainable use of fisheries resources, as well as maritime, economic, and food security (Laffoley et al. 2019). However, to combat IUU fishing and facilitate more effective fisheries management strategies (Cimino et al. 2019), it is essential to have detailed information on fisher behavior and spatial patterns of activity and effort (McCauley et al. 2016). In this context, governments are increasingly investing in monitoring, control, and surveillance systems, including logbooks, patrol vessels, and onboard observers. The most common strategy, however, is the application of vessel monitoring systems (VMS) to observe behavior and compliance of fishing fleets in national waters. Vessel monitoring systems are satellite-based monitoring systems whereby an onboard transmitter relays information on a vessel's identity, location (latitude and longitude), course, and speed to national fisheries

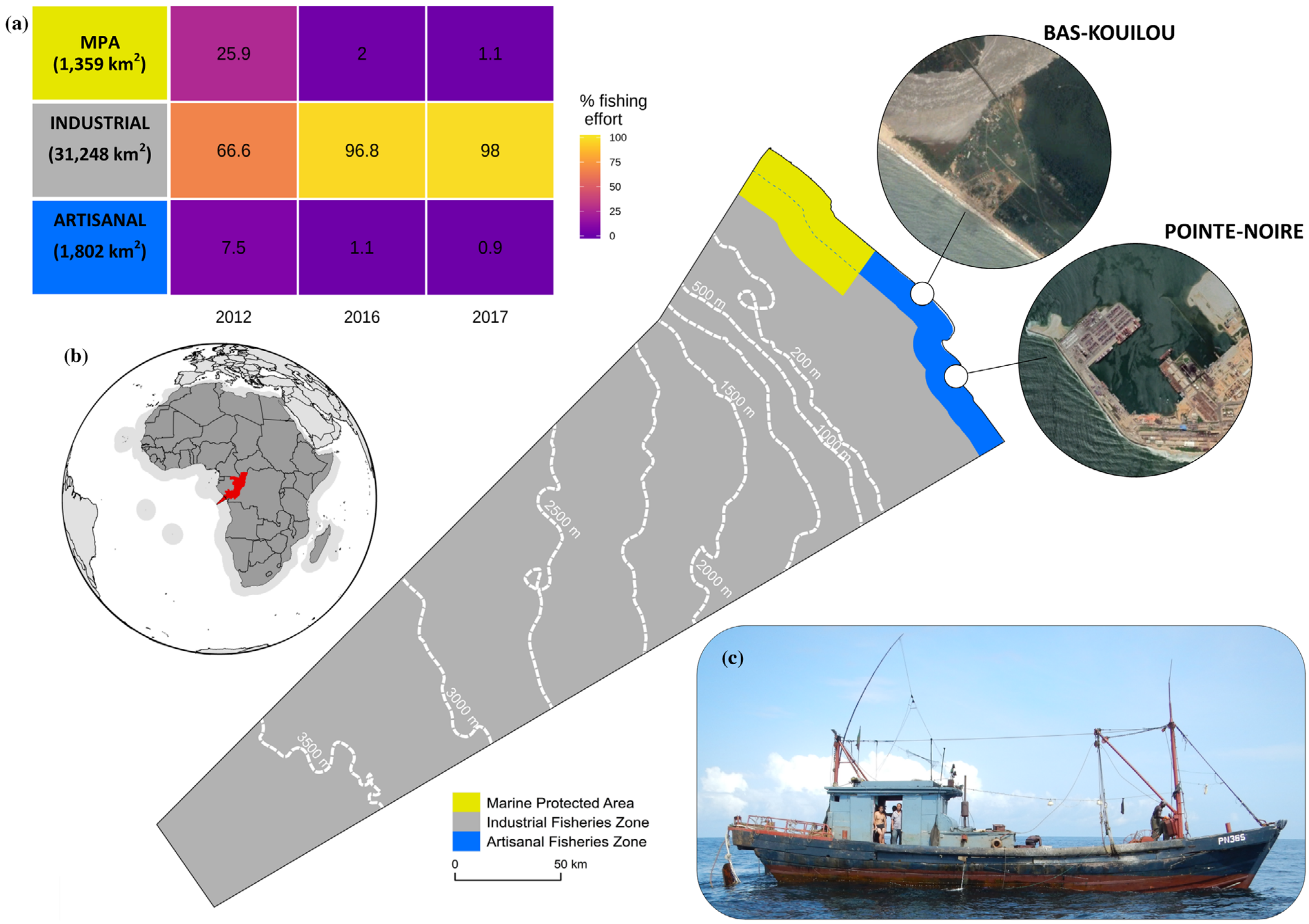

Figure 1. (a) Percentage of fishing effort (time spent fishing per year) for each designated fishing area per year in the Republic of the Congo; (b) location of the Republic of the Congo's Exclusive Economic Zone (blue, artisanal fishing zones; gray, industrial fishing zones; yellow, Conkouati-Douli National Park MPA; insets, major ports of operation of industrial vessels of Bas-Kouilou and Pointe-Noire [source: Google Earth] and bathymetric depth contours [source: GEBCO]); and (c) industrial fishing vessel operating in Congolese waters

authorities, who are the only authorized parties to have access to the information. Vessel monitoring systems offer an opportunity to provide near real-time data that can be used to determine the location of fishing activity and better understand management needs (Kroodsma et al. 2018; Roberson et al. 2019). Vessel monitoring systems, however, are not a legal requirement in all countries, and where it is implemented, few countries have systematic data management. This means that a large proportion of global fishing effort remains undetected.

The Republic of the Congo is one such example, where, despite access to and availability of VMS data, there has been a lack of coordinated data management. Data originated from multiple providers, which results in varying spatiotemporal coverage in fisheries monitoring. We used a multiyear national-scale study to address these data gaps to better understand patterns of fisheries activity by collating historical VMS data; assessing the spatial footprint of industrial fisheries, analyzing fisher behavior with regard to extent and focus of efforts, and evaluating potential drivers of industrial fishing effort, as well as providing a snapshot of the legal and illegal behavior of national and distant-water fleets operating in these waters. Given the growth and expansion of industrial fisheries across much of Africa (Tickler et al. 2018), we sought to provide important insights into the behavior of these fleets that can be used to inform regional policy to help combat IUU fishing and effectively conserve and manage marine resources.

Methods

Study area and fisheries policy

The Republic of the Congo is on the Atlantic coast of Central Africa (EEZ 33,757 km^2) (Figure 1). This region is characterized by strong upwelling (Chukwuone et al. 2009) that is highly productive and thus subject to intense pressure from artisanal and industrial fishing fleets (Belhabib & Pauly 2015b; Belhabib et al. 2015), numbers of which have rapidly expanded in recent times, especially those of the distant-water industrial fleet (Appendix S1). Fishing occurs throughout the year with approximately 110 industrial and 700 artisanal boats ($\sim$240 motorized, $\sim$450 nonmotorized) operating primarily on the continental shelf in Congolese waters (Metcalfe et al. 2017; Momballa 2020). Gear deployment differs between the industrial and artisanal sectors, both in scale and focus, other than fishing for sardinellas, which is targeted by both sectors. Reconstruction of domestic industrial fishing catch is largely dominated by trawlers targeting shrimp, but also by demersal trawling and purse seiners. Although catch levels increased from 2300 to 38,400 t from 1950 to 1975 (Belhabib & Pauly 2015a), catches decreased to <11,000 t in 2010. Belhabib and Pauly (2015b) found that catch from vessels from the Republic of the Congo fishing outside the Congolese EEZ peaked at approximately 37,400 t in 1968 before declining to very low levels by the late 1980s, after which this fleet focused efforts in Congolese waters.

The institutional framework for management of these fisheries is legislated by *Loi no* 2–2000, a key piece of legislation that consists of a set of rules for the management of fisheries resources (DLA Piper 2016). Fundamentally, this legislation establishes 2 fishing zones—artisanal and industrial. The artisanal zone (1802 km^2; 5% of EEZ) extends 6 nautical miles out from the coastline and is reserved exclusively for artisanal fishing vessels. The industrial zone (31,248 km^2; 93% of EEZ) extends from 6 nautical miles out to 200 nautical miles from the coastline, within which industrial fishing vessels registered in the Republic of the Congo and states with which the Republic of the Congo has entered into a fishing agreement can operate legally. In addition, a coastal national park exists (Parc National Conkouati-Douli) in which artisanal fishing is permitted in its community eco-development zone and industrial fishing is prohibited (Figure 1).

Vessel monitoring system data processing

Unprocessed VMS data were provided by CLS (*Collecte Localisation Satellites*) for 2012 (n = 12 months) and ProNet for 2016 (n = 10 months) and 2017 (n = 4 months) and comprised of 984,973 location records (2012: n = 472,354; 2016: n = 412,216; 2017: n = 100,403). Each location record included a vessel identification (ID) code (unique code assigned to each beacon on each vessel), position report (longitude and latitude), and date-time fields. For data provided by ProNet (n = 2 years), additional information was available on the registered owner for each unique vessel ID, thereby allowing records within these years to be assigned as either national or distant-water fleets (DWFs) (i.e., fishing in areas far from country's domestic waters [Appendix S2]). These data sets were then combined and filtered to remove records with no positional information (longitude or latitude); duplicate records; and locations outside the study period (2012, 2016, and 2017) or study area (defined as the Republic of the Congo EEZ [Flanders Marine Institute 2018]). No metadata were available on when fishing trips started and finished; therefore, we derived 24-h vessel transits to describe daily patterns of vessel movements. This was achieved by assigning a unique identifier to all position reports in each 24-h period (00:00 to 23:59 UTC) for each unique vessel ID. To address the problem of uneven sampling and ensure vessel locations were equally spaced in time, piecewise cubic hermite interpolating polynomials were computed for vessel days with >4 locations to standardize locations to 20-min intervals for each unique 24-h transit. Cubic hermite splines were chosen due to increased accuracy for movement data (Tremblay et al. 2006). All vessel locations were then categorized as either night or day based on sunrise and sunset times in the suncalc package (Agafonkin & Thieurmel 2018). This resulted in a combined boat activity data set of 781,370 locations, from which 13,980 24-h daily vessel transits were generated.

Mapping spatiotemporal patterns of fisheries activity

To describe spatiotemporal patterns of vessel activity, we created a fine-scale hexagon grid with a cell resolution of 0.002° longitude and latitude (equivalent to 0.05 km^2). This fine-scale resolution was selected to ensure subsequent analyses did not overestimate the footprint of fisheries activity (Amoroso et al. 2018). We then generated 3 measures from the 24-h daily vessel transit data set: intensity; occupancy; and fishing effort. Intensity was derived by summing the total number of 24-h transits in each cell each year, and occupancy was derived by calculating the total number of days each year (as a proportion) that a vessel was recorded as transiting through each cell, as per Metcalfe et al. (2018). To derive fishing effort, we calculated vessel speed for all locations in each unique 24-h transit and applied a parsimonious speed filter to identify fishing events—defined as 1.5–5.0 knots, as per Witt and Godley (2007). Due to a lack of associated metadata on fishing practices for each vessel ID, it was necessary for the speed filter to incorporate multiple gear types and activities. All locations categorized as fishing within 5 km of ports (Port of Pointe Noire and Bas-Kouilou) (Figure 1) were excluded, resulting in a data set that contained 470,482 locations. This approach was adopted to reduce the likelihood of detecting false positives of fishing, where boats are moving at lower speeds close to port (Lee et al. 2010). Although legitimate fishing activity close to ports may have been removed, this step reduced the need for intensive visual inspection and maximized retention of VMS data (Witt & Godley 2007). Fishing effort was then calculated for all years, night and day, and for the national and distant-water fleets for 2016 and 2017 with a point-summation method, as per Lee

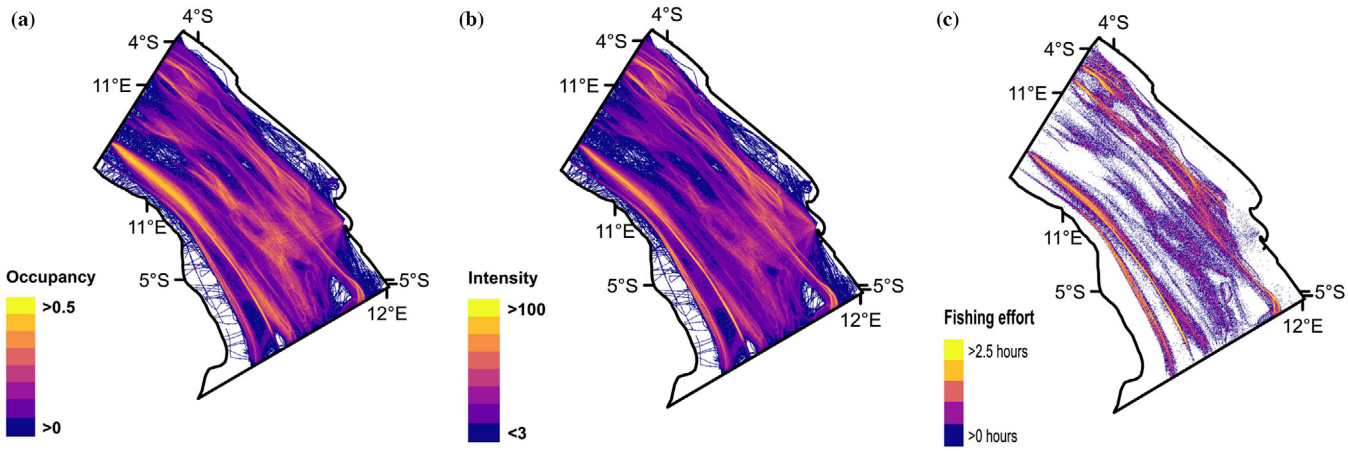

Figure 2. Spatial distribution of industrial fishing activity in Congolese waters shallower than 1000 m: (a) mean vessel occupancy (proportion of days a vessel occupied each cell), (b) mean annual vessel intensity (total number of 24-h transits in each cell), and (c) fishing effort (24-h transits at 1.5–5.0 knots) in hours of fishing effort per grid cell. Resolution: 240 m hexagon grid cell (~0.02° longitude and latitude)

et al. (2010). This involved spatially intersecting the fishing location data set with the hexagon grid, multiplying the number of fishing locations per unique 24-h transit by the interpolated time step (20 min) to provide a metric of time spent fishing per unit area. To account for between-year variability values for each measure (i.e., intensity, occupancy, and fishing effort) were averaged within years (months) and then across years to produce annual composites (Appendix S4).

Characterizing fisher behavior

Most policy and management interventions in fisheries and conservation require detailed information on human behaviors (Fulton et al. 2011), therefore, data on fishing effort were spatially intersected with legally defined fisheries zones and national park boundaries to better understand patterns of resource use and quantify levels of legal and illegal fishing. Finally, to investigate whether fishing effort was driven by proximity to major ports or environmental variables (sea surface temperature and chlorophyll-α concentration), we applied a general additive model (details in Appendix S5). All statistical and spatial analyses were performed in R 3.5.1 (R Core Team 2020).

Results

The industrial fisheries fleet occupied an area of 9576 km^2, equivalent to 28% of the EEZ (Appendix S3), of which an area >100 km^2 (0.32% of the EEZ) was occupied by fishing vessels for more than one-quarter of the year on average (Figure 2a & b). The annual footprint of fishing activity covered 5737 km^2 (17% of the EEZ) (Appendix S3). On average, there were 52,225 h (equivalent to 2176 days per annum) fished (Figure 2c), 73% of which occurred on continental shelf waters shallower than 200 m (Appendix S6).

Temporal investigation revealed an average of 67% of fishing effort was conducted during the day; 70% of this effort took place on the continental shelf (Figure 3 & Appendix S6). For the remaining nocturnal fishing, 77% of this activity occurred on the continental shelf (Figure 3 & Appendix S6). Further analyses by flag state revealed that fishing was dominated by the distant-water fleet, accounting for an average of 95% of total annual effort, 70% of which took place on the continental shelf (Figure 3 & Appendix S6). The national fleet accounted for an average of 5% of annual effort, 63% of which occurred on the continental shelf (Figure 3 & Appendix S6).

Fishing occurred in all zones (industrial, artisanal, and national park) in all years; an average of 87% of annual effort occurred in the industrial zone. An average of 10% and 3% of fishing effort occurred in the national park and artisanal zone, respectively (Figure 1). The distant-water fleet accounted on average for 84% of the annual effort in prohibited areas (national park 92% and artisanal fisheries zone 71%) (Appendix S7).

In terms of exploring potential drivers of fishing effort, environmental variables (sea surface temperature and chlorophyll-α concentration) had no influence on fishing intensity; both sea surface temperature and chlorophyll-α were not retained in the top model (Appendix S8). Distance from major ports was shown to have some influence on fishing intensity. Fishing effort was concentrated close to shore, and peak activity occurred 30–60 km from ports (Appendix S9). Partial plots suggested relatively weak effects; adjusted R^2 was 19% (Appendices S8 and S9).

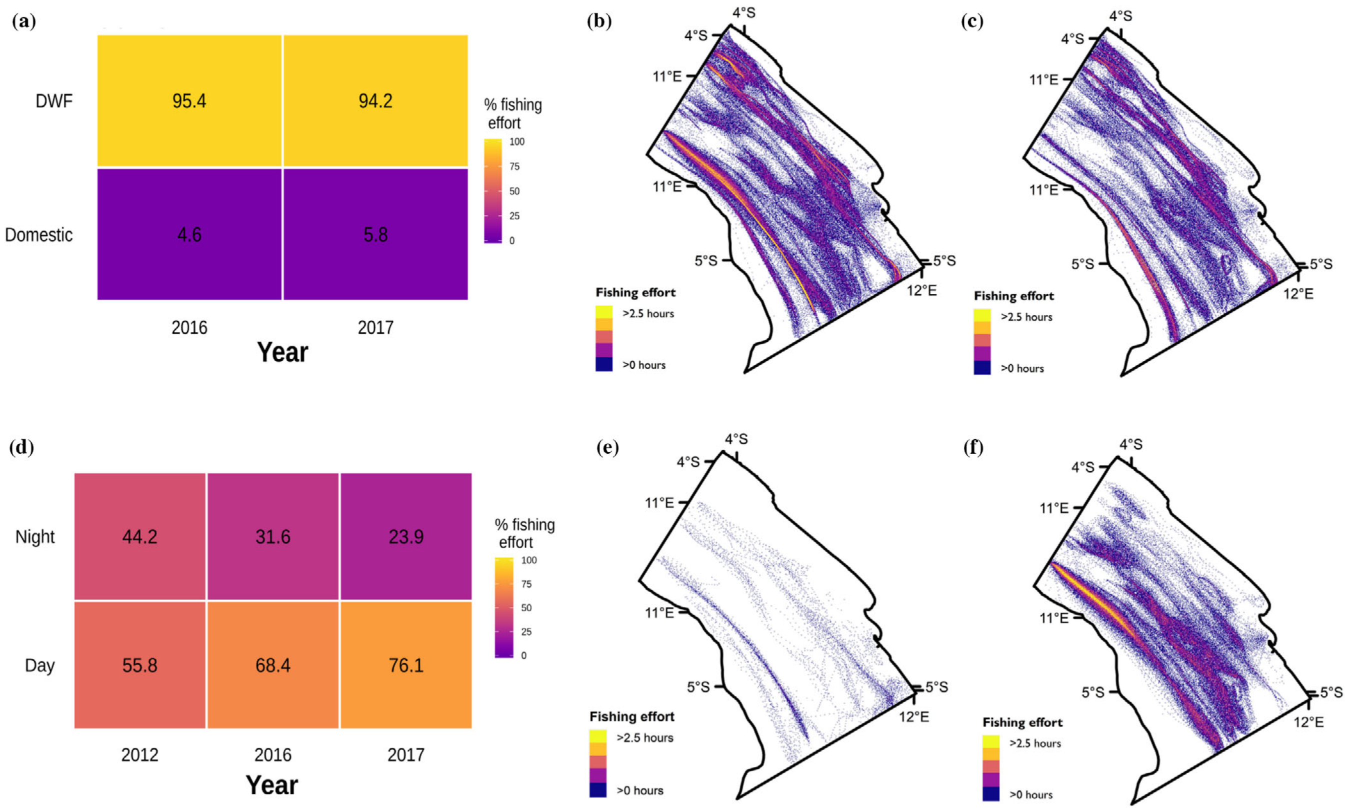

Figure 3. Percentage of total fishing effort per year for (a) flag state of fishing vessels (distant water [DWF] or domestic fleet), and hours of fishing effort (24-h transits at 1.5–5.0 knots) per grid cell for (b) distant water fleet, and (c) domestic fishing fleet. Percentage of total fishing effort per year for (d) time of day fishing occurred, and hours of fishing effort (24-h transits at 1.5–5.0 knots) per grid cell for (e) fishing at night and (f) fishing in the day. Resolution: 240 m hexagon grid cell (~0.02° longitude and latitude)

Discussion

Illegal, unregulated, and unreported fishing remains one of the greatest threats to marine ecosystems in Africa; IUU fishing in the Eastern Central Atlantic is estimated to be responsible for over 30% of the reported catches (Agnew et al. 2009). It has the potent ability to undermine national and regional efforts to manage fisheries, conserve marine biodiversity, and hinder progress toward sustainable development goals, such as poverty alleviation and food security (FAO 2001); anything that undermines human security is considered an explicit threat to national security (Okafor-Yarwood 2020). The capacity of countries to combat IUU fishing across the region, however, is often limited by a lack of detailed information on the activity of industrial fishing vessels.

Despite the sporadic coverage and availability of VMS data for the Republic of the Congo, with only 40–79% of vessels equipped with VMS beacons (Departmental Directorate of Fisheries and Aquaculture for Pointe Noire/Koulou, personal communication), our data provide an important snapshot into recent patterns of industrial fishing activity. More specifically, these data showed that the footprint of the industrial fleet is particularly large relative to the size of the Republic of the Congo's waters, with industrial vessels (i.e., trawlers and purse seiners) using an area of 5737–9567 km^2 per annum, equivalent to between 17% and 28% of the EEZ. Fishing occurs both during the day and night. Much of the activity during these periods is concentrated in the shallow waters of the continental shelf, with these waters alone accounting for 73% of all effort. When coupled with available data on spatial patterns of resource use for the artisanal fleet, which is predominantly restricted to inshore waters (Metcalfe et al. 2017), these findings highlight that much of the fishing effort in the Republic of the Congo is concentrated in a very small area, which exacerbates pressure on marine biodiversity and coastal resources and increased incidence of overlap and potential conflict between artisanal and industrial fleets.

In addition, although our findings showed that much of the effort occurred in the industrial zone and is therefore considered legal, a substantial proportion—as much as 33% (13% on average)—of annual fishing effort was illegal. Illegal fishing occurred inside the limits of the artisanal fishing zone and the national park—the boundaries of which did not appear to serve as an effective deterrent. Analyses of flag state revealed that the distant-water fleet was responsible for the vast majority of the recorded illegal fishing, on average 84% of the total effort in prohibited areas (Appendix S7). The scale of illegal fishing identified, however, is likely to be an order of magnitude greater given that not all vessels were tracked and is likely to have profoundly negative implications for the long-term sustainability of the fisheries sector, as well as economic and food security given that 4.2% of the poorest households nationally and 9% of the coastal population are dependent on the small-scale fisheries as a source of employment (Belhabib et al. 2015) and that 48.8% of the nation's dietary protein is provided by fish products (Béné & Heck 2005). Much of the fishing by distant-water fleets in the Republic of the Congo (and across Africa) is facilitated by, and only possible as a result of, fisheries subsidies, without which fishing in waters far from port of origin would likely become unprofitable (Belhabib et al. 2019; Okafor-Yarwood & Belhabib 2019; Sumaila et al. 2016).Therefore, countries should be committed to end these harmful funding practices to alleviate some of the pressure.

Furthermore, because many coastal developing countries often lack the capacity to fully exploit their national waters, they seek support from foreign countries which benefit by entering into agreements with, or buying fishing licenses from, these coastal states (Okafor-Yarwood et al. 2020). Although such agreements generate income for the coastal country by allowing these distant-water fleets to fish in their EEZs, this revenue is often a fraction of what is generated from the sale of the catch, much of which is exported (Belhabib et al. 2015). There is also often a lack of transparency regarding these joint ventures and bilateral agreements between coastal countries and distant-water operations, which has led to accusations of corruption in many countries (Yozell & Shaver 2019). The paucity of available information about the content and context of these agreements, fleet composition, vessel ownership, and landing statistics makes it challenging to create an accurate depiction of distant-water fleet activities. We described the spatial context of industrial fishing in Congolese waters from licensed vessels, many of which are from distant shores with fisheries agreements (Appendix S1). We observed illegal activity, which raised the question of what vessels without agreements or VMS beacons are doing. Knowledge of catch composition by licensed and unlicensed vessels alike is scarce, so the value, both in terms of remuneration and the spirit in which the agreements were entered into, is not likely matching the intended worth.

Analyses into potential drivers revealed that industrial fishing effort in the Republic of the Congo rapidly decreased beyond 60 km from fishing ports. This may be a reflection of the size, construction, and condition of many of the vessels in the industrial fleet, which are typically between 15 and 30 m in length, wooden hulled, and lack refrigerated cold stores (Figure 1). This may impose restrictions on the distances in which they can safely operate and the amount of catch they can store onboard without compromising the quality and value of their catch. There is no evidence to suggest that fishing is carried out in response to environmental conditions because we found no relationship with ocean productivity or temperature. Given these findings, it is possible that decision making with regard to location and timing of fishing may be determined more by culture, experience, past successes, species presence in particular areas at particular times of the year, more fine-scale environmental conditions, as well as perceived risk of being caught fishing illegally. This emphasizes the need for further social and landing surveys with national and distant-water fleets to better understand motivations and drivers of spatiotemporal aspects of fishing activity.

Ultimately, what our study reveals is that VMS alone is not an effective deterrent and that a major barrier to more pervasive and effective monitoring, control, and surveillance and the principal factor enabling IUU fishing is a lack of capacity to analyze these data (McDonald et al. 2016; Doumbouya et al. 2017; Lindley & Techera, 2017; Belhabib et al. 2019). Unprocessed data do not indicate what activities are being conducted (Mendo et al. 2019). Additionally, establishing strong links within the enforcement chain, from detection to conviction, is imperative if regulations are to lead to compliance. When the value for any link in the enforcement chain approaches zero, overall enforcement likely becomes ineffectual (Arias et al. 2016).

One tool that is increasingly being adopted for surveillance of ocean vessels is AIS. These systems transmit a vessel's position (latitude and longitude), and transmissions are receivable by other vessels, primarily to prevent at-sea collisions. It is legally required on all vessels larger than 300 t that travel internationally, cargo ships larger than 500 t, and passenger ships of all sizes. Automatic identification systems, however, are not mandated for fishing vessels (except EU fishing vessels over 15 m in length and U.S. vessels over 19 m in length [Taconet et al. 2019]), and so there are limitations that hinder insight into fishing activity in regional waters. Many vessels will not carry AIS—the percentage of West African vessels >24 m in length (size most likely to carry AIS) is reported to be approximately 0.6% of total fleet, and vessels of 12–24 m represent 2.4% of the total fleet (FAO 2018). A recent overview of global AIS detection of fishing activity showed very little presence of trawlers and purse seiners in the EEZ of the Republic of the Congo and surrounding countries, leading to a mismatch with landings data for the region (Arrizabalaga et al. 2019). We found that this lack of observation is not down to lack of activity, but more likely due to limited AIS onboard vessels, manipulation of AIS to broadcast misleading activity, or AIS device class—most vessels equipped with AIS use class A devices, whereas some use class B devices (most commonly used by distant-water fleets from China and Taiwan), which has relatively poor reception quality across the region. This gap in observations may lead to a reduced ability to detect fishing activity and much less capacity to detect IUU fishing (Arrizabalaga et al. 2019), which as highlighted here could be filled by national VMS coverage.

The problems we identified are not limited to the Republic of the Congo, and so if the global community is committed to achieving sustainable development goals (SDG) and genuinely wants to help eliminate IUU fishing by industrial vessels along the coast of Africa, then greater cooperation is needed among governments, conservation scientists, practitioners, policy makers, and donors to address the target of SDG17 to strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development. We propose the following objectives to help tackle this issue in the Republic of the Congo and beyond: support the implementation of VMS beacons on all industrial vessels to increase transparency and accountability; establish partnerships to strengthen national capacity to analyze VMS data to inform decisions on the ground; help increase the number of regular patrols targeting known hotspots of illegal fishing to act as a visible deterrent; and support the revision of national fisheries laws to strengthen rules and regulations to align with targets in the Yaoundé Code of Conduct, of which the Republic of the Congo is a signatory. We suggest all these strategies to disincentivize illegal behaviors by reducing the perceived rewards and increasing the perceived risks and effort.

Acknowledgments

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Supporting Information

Appendix S1. Evolution of the industrial fishing fleet in the Republic of the Congo from 1947 to 2018. Solid black line denotes the smoothed estimate from the general additive model (GAM), with light gray shading representing standard error (se).

Appendix S2. Summary of data sources and associated variables available within each year.

Appendix S3. Summary statistics for the footprint of fisheries activity within the Republic of the Congo EEZ calculated for intensity, occupancy, and effort for industrial fleet, national and distant-water fleets, and period of day.

Appendix S4. Schematic diagram of how data were organized for analysis from raw location files to meaningful outputs.

Appendix S5

Appendix S6. Mean number of VMS locations per year categorized as fishing for (A) all fishing activity ($n = 3$ years), (B) time of day (day; night, $n = 3$ years), and (C) flag state of fishing vessels (distant-water fleet [DWF]; domestic fleet, $n = 2$ years). Percentages of fishing occurring on the continental shelf for each categorization of effort shown. Dotted line denotes 200 m depth representing the continental shelf.

Appendix S7. Summary statistics for proportion of fisheries activity carried out by national (domestic) and distant-water fleets (DWFs) for each designated zone within the Republic of the Congo EEZ.

Appendix S8. Summary results of general additive model (GAM) to test for effect of chlorophyll-α concentration (chla; mg m^{-3}), sea surface temperature (SST; °C), or distance from port (km) on fishing effort (mins). Top ranked models after selection for ΔAIC ≤ 6 (Harrison et al., 2018) highlighted in bold.

Appendix S9. (A) Partial effect plot of distance from port (km) plotted as a smoothed fit. Values on the y-axis indicate the effect the variable term is having on the amount of fishing occurring. Solid red lines denote the smoothed estimate from the general additive model (GAM), with blue shading representing standard error (se) around the estimate. Red dots represent the partial residuals from the final general additive model (GAM). (B) Fishing effort predictions from the final GAM retaining only distance from major ports (km). Black lines denote predictions from the GAM with blue shading representing standard error (se). Rug plots show where data were obtained for each variable.

Appendix S10. Data processing steps and associated loss or gain of locations for each year of VMS data available.

Appendix S11. Summary results of pairwise tests of concurvity between variables included in general additive model (GAM; chlorophyll-α concentration (chla; mg m^{-3}), sea surface temperature (SST; °C), and distance from port (dist. from port; km)). Indices are based on idea that a smooth term (f), in the model, can be decomposed into a part (g) that lies completely in the space of one or more other terms in the model, and a remainder part that is completely within the term's own space.

Worst; largest value that the square of g/f could take for any coefficient vector, O*bserved*; value of the square of g/f according to the estimated coefficients, and *Estimate*; squared F-norm of the basis for g divided by the F-norm of the basis for f. It is a measure of the extent to which the f basis can be explained by the g basis.

Appendix S12. Semi-variogram plot to test for spatial autocorrelation within residuals of the general additive model (GAM).

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