

RESEARCH ARTICLE

Using satellite AIS to improve our understanding of shipping and fill gaps in ocean observation data to support marine spatial planning

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Abstract

1. A key stage underpinning marine spatial planning (MSP) involves mapping the spatial distribution of ecological processes and biological features as well the social and economic interests of different user groups. One sector, merchant shipping (vessels that transport cargo or passengers), however, is often poorly represented in MSP due to a perceived lack of fine-scale spatially explicit data to support decision-making processes.
2. Here, using the Republic of Congo as an example, we show how publicly accessible satellite-derived automatic identification system (S-AIS) data can address gaps in ocean observation data for shipping at a national scale. We also demonstrate how fine-scale (0.05 km² resolution) spatial data layers derived from S-AIS (intensity, occupancy) can be used to generate maps of vessel pressure to provide an indication of patterns of impact on the marine environment and potential for conflict with other ocean user-groups.
3. We reveal that passenger vessels, offshore service vessels, bulk carrier and cargo vessels and tankers account for 93.7% of all vessels and vessel traffic annually, and that these sectors operate in a combined area equivalent to 92% of Congo's exclusive economic zone—far exceeding the areas allocated for other user groups (conservation, fisheries and petrochemicals). We also show that the shallow coastal waters and habitats of the continental shelf are subject to more persistent pressure associated with shipping, and that the potential for conflict among user groups is likely to be greater with fisheries, whose zones are subject to the highest vessel pressure scores than with conservation or petrochemical sectors.
4. *Synthesis and applications.* Shipping dominates ocean use, and so excluding this sector from decision-making could lead to increased conflict among user groups, poor compliance and negative environmental impacts. This study demonstrates how satellite-derived Automatic Identification System data can provide a comprehensive mechanism to fill gaps in ocean observation data and visualise patterns of vessel behaviour and potential threats to better support marine spatial planning at national scales.

KEYWORDS

Africa, automatic identification system, Congo, data visualisation, marine spatial planning, shipping, threat mapping, vessel movement

1 | INTRODUCTION

Oceans remain the least observed part of our planet, and so to support more effective marine spatial planning (MSP) and ecosystem-based management (EBM), there is an urgent need to fill gaps in ocean observation data for several user groups, such as fisheries and shipping (McCauley et al., 2016). Globally, there are an estimated 150,000 merchant ships (vessels that transport cargo or passengers), with the international shipping industry responsible for the carriage of c. 90% of world trade and c. 60% of the world's oil and fuel supplies (UNCTAD, 2016). Although shipping is considered the most carbon-efficient form of transport, it accounts for 2.7% of annual global greenhouse gas emissions and contributes >10% of total marine pollution (World Shipping Council, 2016), including discharge of ballast water, waste and hazardous materials, invasive species, physical damage to habitats, air and noise pollution and collisions with wildlife (Bax, Williamson, Agüero, Gonzalez, & Geeves, 2003; Burgherr, 2007; Clark et al., 2009; Laist, Knowlton, Mead, Collet, & Podesta, 2001). Consequently, mapping dynamic patterns of human activity, such as the movement of maritime vessels, is seen as an essential step to better inform the management of marine ecosystems and effectively mitigate current and future threats from shipping on our oceans (Robards et al., 2016).

To date, the only available data that can be used to analyse historical and/or track maritime vessel movements in real time (excluding fisheries, which have also adopted vessel monitoring systems, or VMS) is very high frequency (VHF) universal automatic identification system, or AIS (IMO, 2002). AIS is a system that broadcasts information on a vessel's identity, position, course and speed "among other attributes" to receivers on other ships (ship-to-ship) or land-based receiving stations (ship-to-shore) and is now a mandatory system under provisions of the International Maritime Organization (IMO). Since 2004, the IMO requires that all ships >300 gross tonnage engaged on international voyages, cargo ships >500 gross tonnage not engaged on international voyages and all passenger ships irrespective of size should be fitted with AIS (IMO, 2002). However, despite only being a requirement for large vessels, many small craft may be required to carry AIS (e.g. fishing vessels >15 m in the European Union; Natale, Gibin, Alessandrini, Vespe, & Paulrud, 2015) or employ AIS for collision avoidance. As a consequence, this system produces a relatively rich data stream describing ship traffic, and hence, land-based AIS receiving stations have become an important tool for maritime authorities to monitor vessel traffic.

AIS, however, has limitations, with signal transmission to receiving stations restricted to "line of sight," typically 50 nautical miles (Ball, 2013; Shelmerdine, 2015). Information on vessel movements in offshore waters or areas isolated from ports and shorelines are therefore often missing, and hence, satellite-derived automatic

identification system, or S-AIS, was developed to collect and process vessel transmissions (hereafter, position reports) beyond the reach of land-based receiving stations. S-AIS is thus ideally suited to remote regions, or where infrastructure is lacking, thereby providing maritime authorities with the potential to monitor vessel movements out to the limit of their exclusive economic zone, or EEZ (200 nautical miles), over which a nation has certain sovereign rights. S-AIS is also subject to limitations associated with satellite coverage; furthermore, in areas where vessel traffic is very dense (>2,500 vessels), the satellite can become saturated and incapable of resolving "collided" position reports (see Ball, 2013 for a description of the application and limitations of S-AIS). Nonetheless, S-AIS data provide the most comprehensive view of maritime traffic to date.

The Republic of Congo (hereafter, Congo-Brazzaville), situated on the west coast of Central Africa, is a prime example of where S-AIS data can play an important role in vessel monitoring. Offshore petroleum extraction is vital to the economy of Congo-Brazzaville, accounting for an estimated 75% of government revenue (IMF, 2014). These waters are thus the focus of considerable vessel activity with petrochemical exploration, exploitation, storage and associated support services, transport and supply vessels operating from the recently expanded port of Pointe Noire up to 130 km offshore, beyond the range of land-based receiving stations (Figure 1). Congo-Brazzaville's EEZ is also situated within the Guinea Current Large Marine Ecosystem, a globally significant marine region and one of the four major eastern boundary current upwelling zones (Figure 1). These waters are thus some of the most productive waters in the world, and hence support a growing fishery sector, which plays an important role in supporting livelihoods, poverty alleviation and food security by providing a crucial source of income and dietary protein (Belhabib, Sumaila, & Pauly, 2015). Additionally, these waters host a number of globally important populations of large marine vertebrates, including marine mammals (Collins, 2015; Rosenbaum, Maxwell, Kershaw, & Mate, 2014; Weir & Collins, 2015) and sea turtles (Godgenger et al., 2009; Pikesley et al., 2013), many of which are protected.¹ The small size (39,611 km²) and narrow shape of Congo-Brazzaville's EEZ (c. 154 km at its widest point) has thus led to competing demands by multiple sectors for access to marine space, including fisheries, petrochemicals, mining and conservation (Figure 1). As a consequence, the potential for conflict among user groups and environmental problems is great, particularly on the continental shelf where there are more overlapping claims for space than in offshore waters.

Acknowledging the need for a coordinated approach to the management of the marine environment Congolese decision-makers and

¹Order No. 6075 establishing animal species fully and partially protected by Law No. 48/83 21/04/1983, which cannot be killed, captured, detained, transported, commercialised, imported or exported, with the exceptions of protecting people or for scientific purposes.

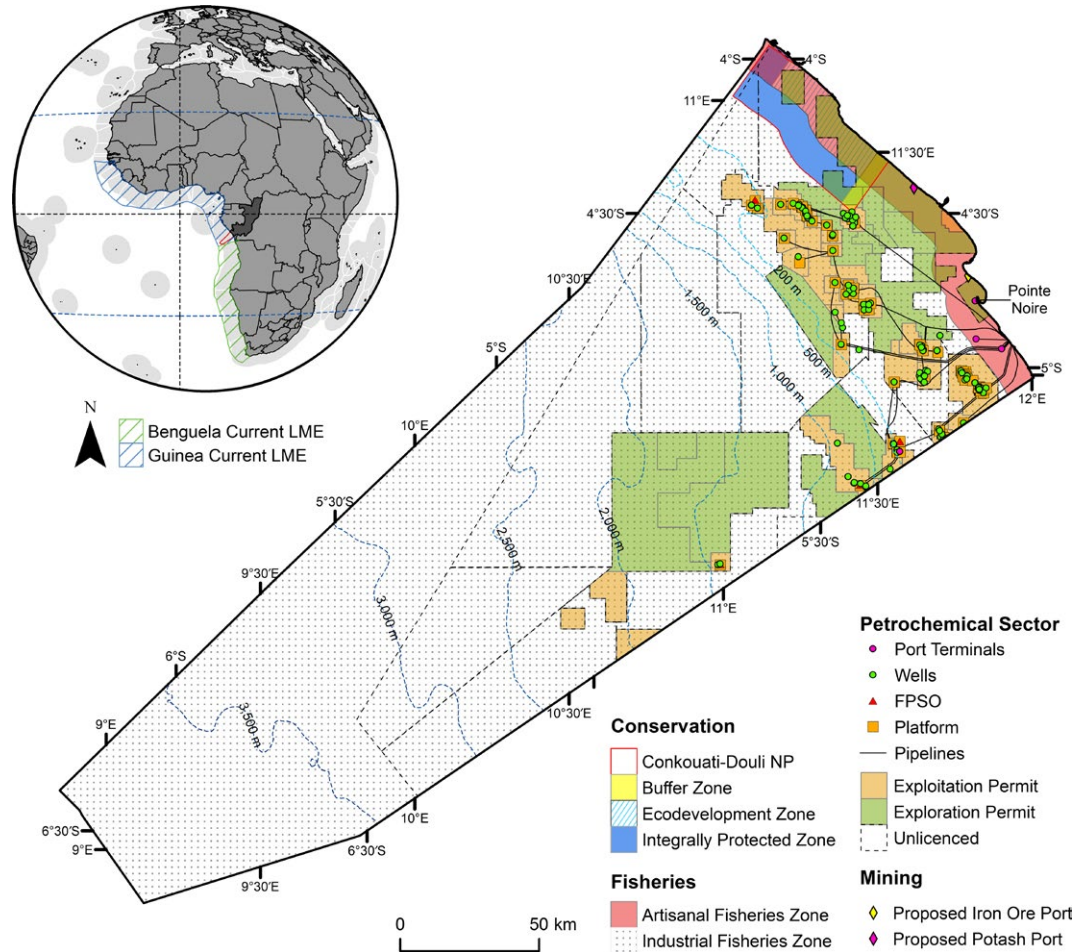


FIGURE 1 Location of Congo-Brazzaville on the west coast of Central Africa and overlapping human uses within its exclusive economic zone [Colour figure can be viewed at wileyonlinelibrary.com]

non-governmental organisations is showing increased interest in developing a marine spatial plan that incorporates multiple user groups, addresses commitments to reduce biodiversity loss, promotes sustainable use, and improves the status of ecosystems and their benefits to people (CBD, 2010). Whilst there have been a number of developments in mapping small-scale fisheries in Congo-Brazzaville (Metcalf et al., 2017), information about the spatiotemporal distribution of maritime vessels in territorial and offshore waters is lacking. Here, we attempt to address these crucial data gaps using S-AIS to map spatial patterns of maritime vessel activity. Furthermore, we show for the first time how fine-scale data layers derived from S-AIS data can be used to generate maps of vessel pressure to identify the potential threat posed by different vessel types across marine ecosystems, habitats and human uses, thereby providing an indication of patterns of impact on the marine environment and potential for conflict with other ocean user-groups. Ultimately, the outputs derived from S-AIS data demonstrated herein can be used to better: (1) visualise vessel behaviour for the different vessel types that comprise the shipping sector; (2) inform decision-making processes that affect economic, environmental, safety and sociocultural interests, (3) identify and mitigate environmental impacts; and (4) minimise conflict among competing sectors and facilitate collaboration among user groups.

2 | MATERIALS AND METHODS

2.1 | S-AIS data processing

Decoded S-AIS data for vessels operating in Congo-Brazzaville's EEZ were obtained from © 2018 exactEarth Ltd (<http://www.exactearth.com/>) for each day between 1 January 2012 and 31 December 2014 ($n = 1,096$ daily files). Location data, hereafter vessel position reports (i.e. longitude, latitude WGS1984; decimal degrees), were accompanied by additional information, including static information programmed into the AIS system when commissioned (e.g. MMSI, ship name and type), dynamic outputs based on the vessels sensors (e.g. longitude, latitude, speed, course and time stamp) or voyage-related information (e.g. moored/underway, destination and draught), as described in detail by the International Maritime Organization (IMO, 2002).

AIS position reports are often subject to positional and navigational status errors associated with faulty equipment, human-related error on installation and omitted values or information prior to or during voyages (Harati-Mokhtari, Wall, Brooks, & Wang, 2007; HELCOM, 2008). Daily files for each year were therefore combined into a global dataset and filtered to extract fields with a high

reliability, as described by Shelmerdine (2015) and Fiorini, Capata, and Bloisi (2016). For each position report, these fields were the associated Maritime Mobile Service Identifier (MMSI) number, positional information, navigation status and time stamp. Several approaches have been developed to process (and visualise) AIS data, each of which are deemed to have advantages and disadvantages (Fiorini et al., 2016). Here, we adopted a quality control procedure that combined several techniques described by the Marine Management Organisation (MMO, 2013), Coomber et al. (2016) and (HELCOM, 2008) to remove potentially erroneous or incorrect position reports. This involved removing position reports that: (1) were located outside of Congo-Brazzaville's EEZ as defined by VLIZ (2014); (2) included no positional information (longitude or latitude); and (3) had an invalid MMSI number. The latter included MMSIs with more or fewer than the required nine digits, or where the codes were of the correct length but outside the correct numerical range (i.e. >2xxxxxxx and <8xxxxxxx); these were associated with land-based receiving stations, search and rescue aircraft, handheld VHF transceivers or search and rescue transponders.

To assign vessel information to each position report, we created a database based on the unique MMSI numbers that are assigned to each vessel. Information associated with each MMSI, such as the vessels flag state, IMO number, year of construction, vessel type, dimensions and weight, were sourced from several online databases. To facilitate reporting, each MMSI was assigned to 1 of 11 vessel categories (i.e. unassigned, non-port service craft, port service craft, military and law enforcement, bulk carrier and cargo vessels,

tankers, offshore service vessels, research, fishing, passenger and recreation vessels; Table 1) and merged with the global dataset of AIS position reports. Vessel categories were adapted from the Marine Management Organisation (MMO, 2013) and derived from vessel types and industries associated with unique MMSI numbers (Table 1).

2.2 | Spatial distribution of vessel activity

The principal application of AIS data is to generate a transit line dataset, whereby lines generated from sequential position reports are used to represent a vessel's movement (Coomber et al., 2016; MMO, 2013). This requires information on each unique voyage (i.e. destination, departure and expected time of arrival) to add metadata to each position report (MMO, 2013). Initial quality checks, however, revealed that the S-AIS data were missing dynamic voyage-related information, which is used to identify unique transits for each vessel. To address this limitation, we generated 24-hr vessel transits; this involved assigning a unique identifier to all position reports associated with each unique MMSI within each 24-hr period (00:00 a.m. to 23:59 p.m.; UTC). Each 24-hr dataset thus likely reflects a segment of a larger journey. To facilitate data handling and storage and increase the speed of subsequent processing, we filtered each 24-hr vessel transit prior to converting to transit lines to reduce the number of position reports and reflect the path that was travelled by each vessel when underway (referred to as transit simplification or thinning; MMO, 2013). For each unique 24-hr vessel transit, this involved removing position reports that identified

TABLE 1 Vessel categories adapted from the Marine Management Organisation (MMO 2013) and derived from vessel types and industries associated with unique MMSI numbers for Congo-Brazzaville

Group	Vessel types	Category
0	Unspecified, unknown MMSI, other type	Unassigned
1	Search and rescue vessels, towing vessels, medical transports and hospital ships, resolution 18 ships, repair vessels	Non-port service craft
2	Tugs, pilot vessels, pollution control vessels, standby safety vessels, firefighting vessels, port/pilot tenders	Port service craft
3	Military (naval) vessels and warships, patrol vessels, port police	Military and law enforcement
4	Bulk carrier, cement carrier, self-discharging bulk carrier, vehicles carrier, wood chips carrier, barge, cargo ship, container ship, deck cargo ship, dry cargo, general cargo ship, heavy lift ship, heavy load carrier, landing craft, roll on-roll off cargo ship, refrigerated (reefer) cargo ship	Bulk carrier and cargo vessels
5	Asphalt/bitumen tanker, bunkering tanker, chemical/oil products tanker, crude oil tanker, floating, production storage offloading (FPSO) tanker, liquefied natural gas (LNG) tanker, liquefied petroleum gas (LPG) tanker, shuttle tanker, tanker	Tankers
6	Accommodation vessels, anchor handling tug supply, anchor handling vessel, cable layer, crane ship, deep sea supply vessel, dive vessel, dredger, drilling barge/rig/ship, floating crane, maintenance platform, multipurpose offshore vessel, offshore construction vessel, offshore support vessel, offshore tug, offshore supply ship, pipe layer, platform jackup rig, platform supply vessel, service ship, speciality diving vessel, supply ship, supply tender, utility vessel, well stimulation vessel	Offshore service vessels
7	Research vessels, survey vessels, survey support vessels	Research vessels
8	Fish carrier, fish factory ship, fishing vessel, trawler	Fishing vessels
9	Crew boats, ferries, passenger ships, surfer, high speed craft (fast passenger transports)	Passenger vessels
10	Pleasure craft, sailing vessels, yachts	Recreation vessels

the vessel as either being at anchor or moored (i.e. navigation status codes 1 and 5 respectively), retaining only 24-hr vessel transits with >1 position report (required to generate lines) and applying a distance threshold to remove consecutive position reports that were <100 m apart ($M \pm SD$: $24.9 \pm 1.4\%$ position reports retained; Table S1). A 100 m threshold was selected as sensitivity analyses revealed that 50 m employed per MMO (2013, 2014) was not as effective at removing position reports associated with vessels classified as underway that were swinging at anchor prior to departing.

To illustrate the spatiotemporal distribution of vessel activity, we created a fine-scale raster grid with a cell resolution of 0.002-degree longitude and latitude (equivalent to 0.05 km²; $n = 807,853$ cells). This resolution was selected as exploratory analyses revealed that it provided a more accurate representation of the spatial footprint and patterns of vessel activity (Figure S1). For each vessel category ($n = 11$), each year ($n = 3$) we calculated two metrics: (1) intensity and (2) occupancy. Intensity was derived by summing the total number of 24-hr transits in each cell each year. 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 ($n = 366$ days in 2012; and $n = 365$ days in 2013 and 2014). The advantage of identifying occupancy rather than simply identifying the number of vessel transits in a particular area is that it provides a greater understanding of vessel behaviour—which areas are consistently utilised and which are not—can convey important information about where key shipping routes are located for different sectors. To account for temporal variability in intensity and occupancy, we averaged across the values for each cell for 2012–2014 ($n = 3$ years) to create annual composites for each metric. For each vessel category, we then scaled annual composites of intensity by occupancy and normalised the resulting outputs to a scale ranging between 0 and 1 to generate a pressure score for each cell (Equation 1; adapted from Halpern et al., 2008). These static visualisations of the spatial distribution of vessel pressure are thus analogous to putative threat maps (Tulloch et al., 2015); where for example, we can assume that a cell with a high level of occupancy and high intensity of maritime vessel activity is subject to greater pressure and so more likely to experience a greater potential for negative impacts than a cell with a low level of occupancy and low intensity of maritime vessel activity (Figure S2 and Table S2).

$$P_c = \ln(O_c * I_c) \quad (1)$$

where P_c is mean annual pressure generated by shipping in each cell, c , which is the natural logarithm of O_c , mean annual occupancy in each cell, multiplied by I_c mean annual intensity in each cell.

Effective governance of the oceans requires detailed information on the spatial distribution and potential impact of human activities. Here, we conducted five spatially explicit analyses that demonstrate how S-AIS data can be used to quantify the potential threat posed by vessel activity on marine ecosystems, habitats and human uses—a key requirement in MSP and structured decision-making (Douvere, 2008; Tulloch et al., 2015). First, we

highlight the physical characteristics of the areas that are exposed to the greatest pressure and thus putative threats from vessel activity. To do this, we converted the fine-scale raster maps of vessel pressure for each vessel category to xy spatial points at their centre (longitude, latitude WGS1984; decimal degrees). We then assigned offshore distance (km) and depth (m) values to each point using coastline data extracted from VLIZ (2014) and General Bathymetric Chart of the Oceans (GEBCO)-gridded dataset respectively (Weatherall et al., 2015). The resulting values for each point were then reclassified into one of 40 depth (100 m increments) and offshore distance (10 km increments) classes to aid data visualisation. For each combination of offshore distance and depth values, we then calculated the average pressure score. Second, we used the global geomorphology of the oceans dataset (Harris, Macmillan-Lawler, Rupp, & Baker, 2014) to identify which marine ecosystem is subject to the greatest pressure within and across sectors. This involved calculating the proportion of Congo-Brazzaville's continental shelf, slope and abyss that falls within each pressure class. Third, we estimated the potential threat to 27 broadscale-seabed habitat types (Methods S1) by calculating the mean vessel pressure across all cells, weighted by cell area, per habitat, as well as the proportion of each habitat type subject to vessel pressure. Fourth, we estimated the potential for conflict between shipping and other ocean user-groups by calculating the mean vessel pressure across all cells, weighted by cell area, per conservation, fisheries and petrochemical zone ($n = 8$) as well as the proportion of each zone subject to vessel pressure. Finally, to understand the spatial footprint of shipping relative to all other activities, we calculated the percentage of the EEZ subject to vessel activity for each vessel category (individually and combined) and present our results relative to the areas claimed (based on legislation) for other ocean-based activities (e.g. conservation, fisheries and petrochemicals; Figure 1).

S-AIS data processing and spatial analyses were performed using *fields*, *geosphere*, *plot3D*, *raster*, *rgdal*, *rgeos*, *SDMTools*, *shapefiles*, *spatialEco* and *sp* packages in the statistical software R (R Core Team, 2016).

3 | RESULTS

Between 2012 and 2014, the annual number of unique MMSI numbers (equivalent to unique vessels) recorded in Congo-Brazzaville's EEZ ranged between 1,701 and 1,975 ($M \pm SD$: $1,828 \pm 138$; Table S3) and accounted for between 22,052 and 31,293 24-hr vessel transits ($M \pm SD$: $26,860 \pm 4,632$; Table S3). Of the 11 vessel categories, bulk carrier and cargo vessels and tankers represented $75.2 \pm 1.2\%$ of all vessels operating annually ($M \pm SD$ $44.7 \pm 1.2\%$ and $30.4 \pm 1.8\%$ respectively; Table S3). However, despite the dominance of commercial vessels, bulk carrier and cargo vessels and tankers represented only $29.6 \pm 2.8\%$ of 24-hr vessel transits recorded annually ($M \pm SD$ $17.2 \pm 0.9\%$, and $12.4 \pm 2.2\%$ respectively; Table S3). The two sectors that accounted for the greatest

activity were offshore service vessels and fast passenger ferries (i.e. crew boats for the petrochemical industry), which accounted for $63.6 \pm 1.9\%$ of all 24-hr vessel transits ($M \pm SD$ $40.2 \pm 2.0\%$ and $M \pm SD$ $23.4 \pm 3.5\%$ respectively; Table S3); despite only accounting for $18.6 \pm 1.6\%$ of the vessels operating annually (Table S3). Given that the remaining seven vessel categories combined (i.e. unassigned, non-port service craft, port service craft, military and law enforcement, research, fishing and recreation) accounted for only 6.3% of all unique MMSI numbers and 24-hr vessel transits (Table S3), the subsequent analyses focused on the four largest sectors (offshore, passenger, bulk carrier and cargo vessels, and tankers), which accounted for 93.7% of all unique MMSI numbers and 24-hr vessel transits (Table S3).

Analysis of the spatial distribution of vessel activity revealed that the intensity of vessel transits, annual occupancy and associated pressure was greatest in shallow waters (<500 m) close to the coast (<100 km) for all vessel types (Figures 2 and 3; see Figures S3–S6 for high-resolution vessel pressure maps). However, the data revealed that there are several shipping routes for tankers located in deeper waters (c. 2,000 m) further offshore (c. 150 km), that are subject to

similarly high levels of pressure experienced in shallow coastal waters (Figure 3).

Of the three marine ecosystems assessed (continental shelf, slope and abyss), the greatest pressure scores (defined as >0.5) were recorded on the continental shelf across all sectors (Figure 4). For offshore service vessels, passenger vessels, bulk carrier and cargo vessels and tankers, 26.7%, 16.9%, 7.0% and 7.9% of the shelf area, respectively ($M \pm SD$: $14.6 \pm 9.2\%$), are exposed to pressure scores >0.5 (Figure 4). This indicates that these areas are subject to high levels of vessel activity and occupancy throughout the year. The slope and abyss were subject to the least pressure of the three ecosystems, with only 1.3%, 1.5%, 0.3% and 2.2% ($M \pm SD$: $1.3 \pm 0.8\%$) and 0.0%, 0.0%, 0.0% and 1.5% ($M \pm SD$: $0.4 \pm 0.7\%$) of these areas exposed to pressure scores >0.5 for offshore, passenger, bulk carrier and cargo vessels and tankers respectively (Figure 4).

When assessing the potential threat to the 27 broadscale-seabed habitat types, the greatest pressure scores were associated with shallow water and shelf habitats located within the infralittoral, circalittoral and upper slope across all sectors (Figure 5). However, whilst the analyses revealed that shallow water habitats within the

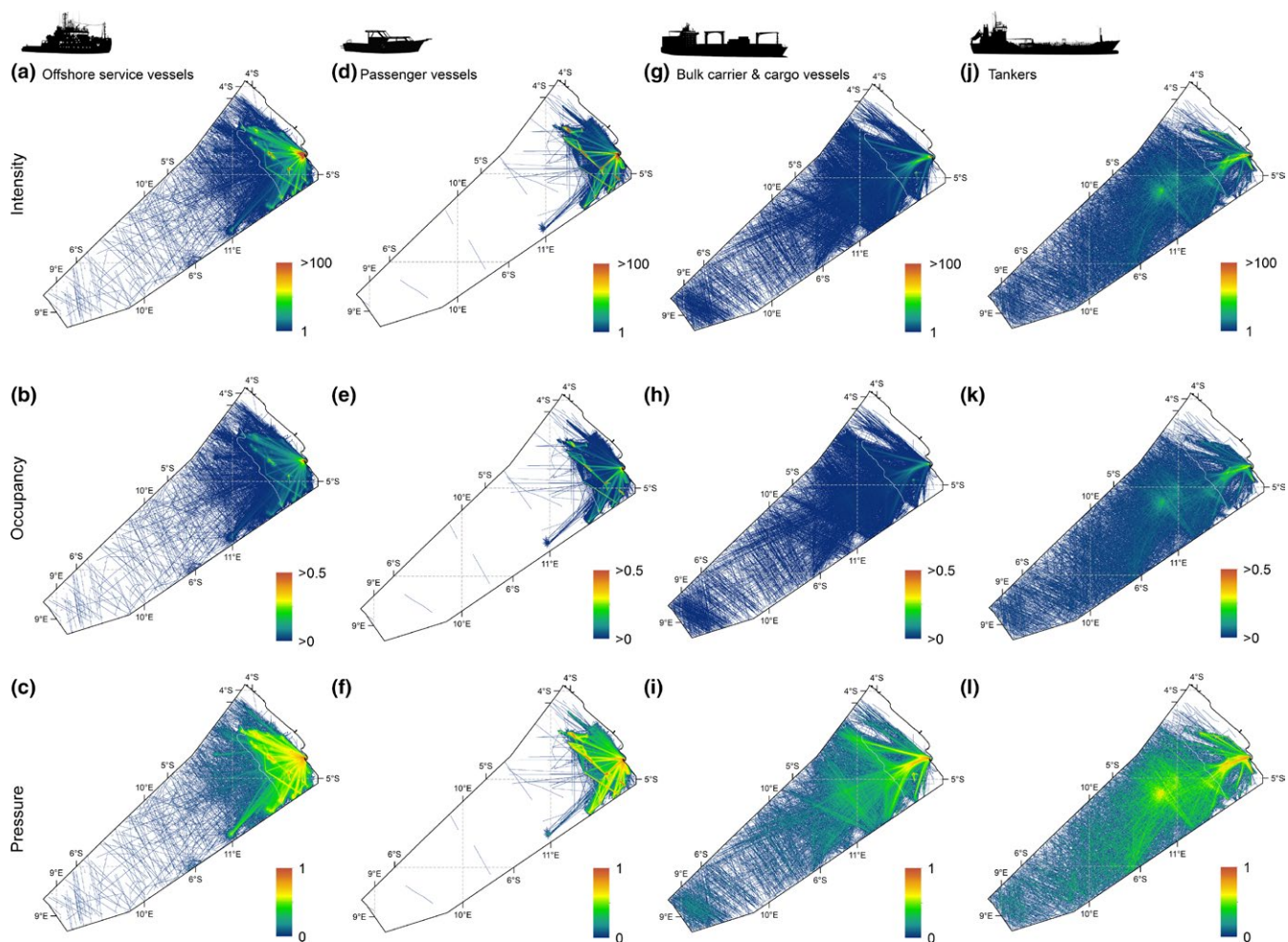


FIGURE 2 Mean annual vessel intensity, occupancy and pressure between 2012 and 2014 ($n = 3$ years) for: (a–c) offshore service vessels; (d–f) passenger vessels; (g–i) bulk carrier and cargo vessels; and (j–l) tankers at a 0.002-degree longitude and latitude cell resolution. See Figure S3–S6 in supporting information for higher resolution pressure maps [Colour figure can be viewed at wileyonlinelibrary.com]

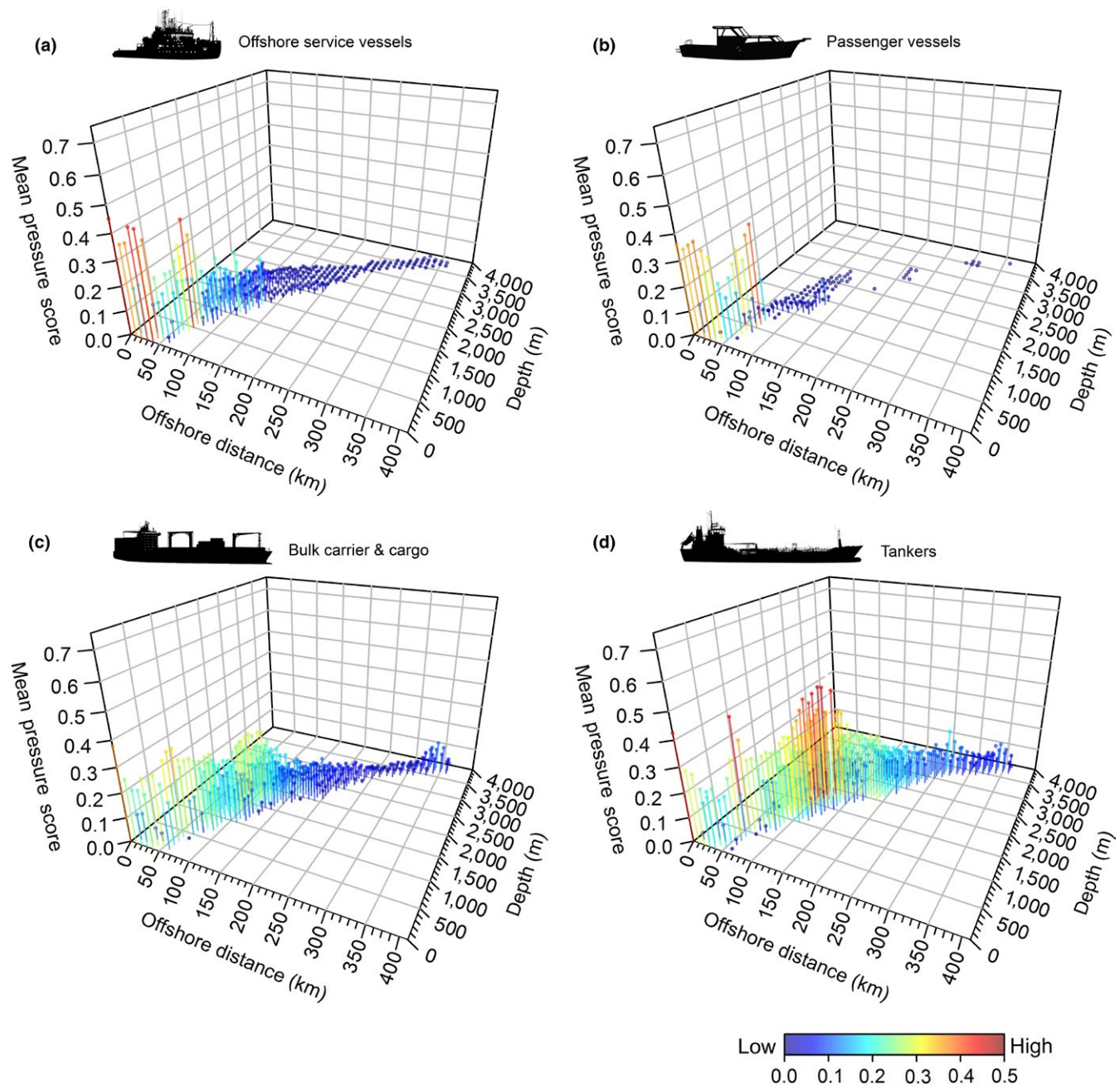


FIGURE 3 Average annual pressure score for each offshore distance and depth class ($n = 40$ classes) for: (a) offshore service vessels; (b) passenger vessels; (c) bulk carrier and cargo vessels; and (d) tankers. Note, to aid data visualisation, only lower values for x and y axis labels are presented [Colour figure can be viewed at wileyonlinelibrary.com]

infralittoral zone were typically subject to more intense vessel pressure, this generally occurred within a smaller proportion of their respective habitat areas ($M \pm SD$ 0.56 ± 0.34 ; Figure 5) compared to habitats located within the circalittoral (0.92 ± 0.07), upper slope (0.93 ± 0.07), upper bathyal (1.0 ± 0.01), mid bathyal (0.98 ± 0.04), lower bathyal (0.97 ± 0.04) and abyssal zones (0.86 ± 0.08 ; Figure 5). Finally, when assessing the potential for conflict with other ocean user-groups, the data revealed that the lowest vessel pressures were located within conservation areas (Figure 6), and that a smaller proportion of the respective zones within conservation

areas were subject to vessel pressure ($M \pm SD$ 0.44 ± 0.32 ; Figure 6) than fisheries (0.72 ± 0.33) or petrochemical zones (0.94 ± 0.04 ; Figure 6). The artisanal fisheries zone was, however, associated with the highest vessel pressures across all existing zones (Figure 6).

4 | DISCUSSION

MSP is increasingly recognised as an important management tool that provides a comprehensive framework for managing multiple activities

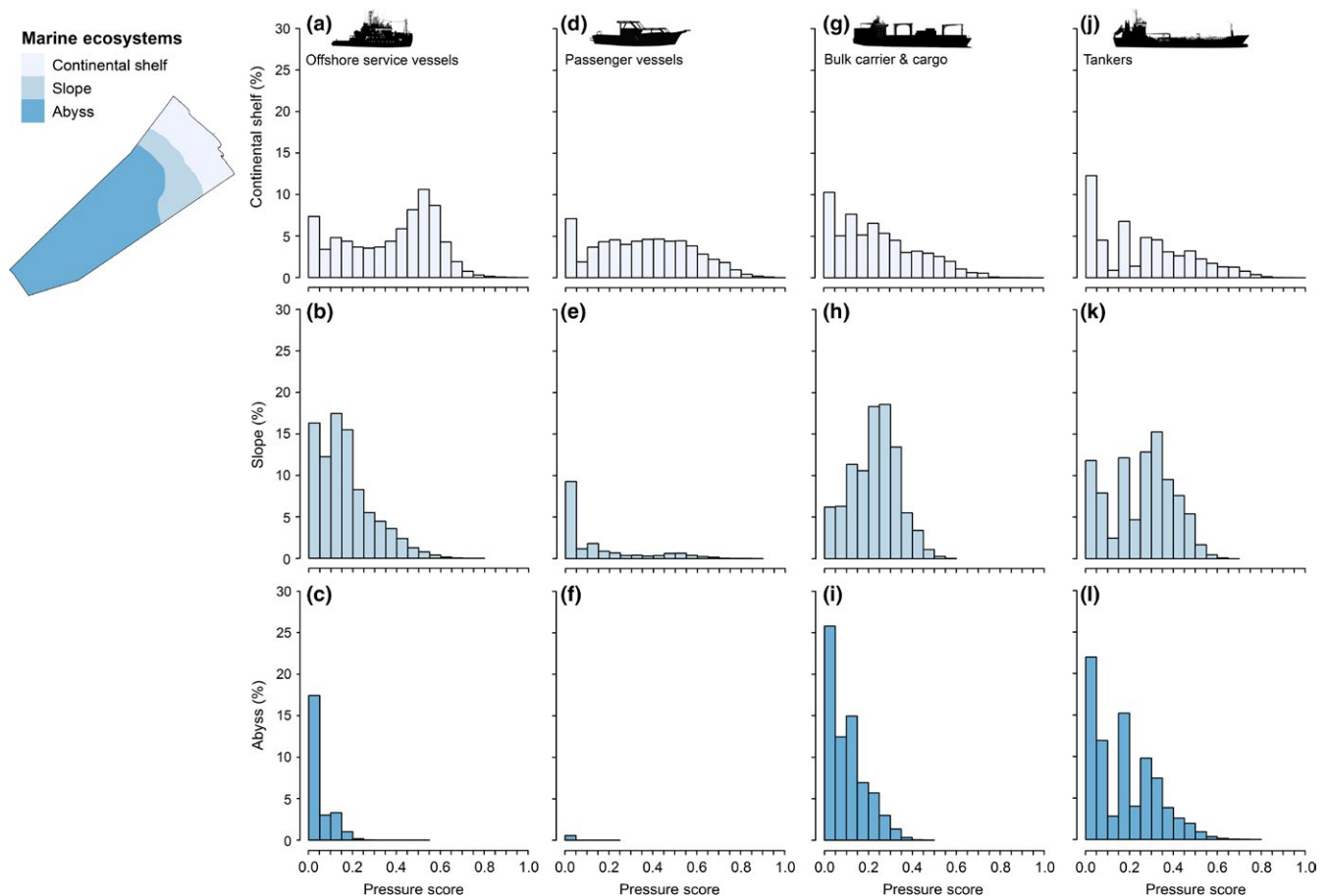


FIGURE 4 Histogram of pressure scores depicting the percentage of the continental shelf, slope and abyss that falls within each category for: (a–c) offshore service vessels; (d–f) passenger vessels; (g–i) bulk carrier and cargo vessels; and (j–l) tankers. Histogram bars are in bins of 0.05 intervals [Colour figure can be viewed at wileyonlinelibrary.com]

within the marine environment (Douvere, 2008). A key stage underpinning MSP involves working with relevant stakeholders to map the spatial distribution of ecological processes and biological features as well the socioeconomic interests of different user groups (Douvere, 2008). The acquisition of such data is designed to help identify multiple, interactive and often cumulative stressors on the marine environment (Ban, Alidina, & Ardrón, 2010; Halpern et al., 2008) as well as spatially separate incompatible activities and minimise conflict among user groups (Crowder et al., 2006). When considering human activities, MSP processes typically have good access to fine-scale spatial data describing the distribution of natural resource exploitation for aquaculture, industrial fisheries (through VMS data), petrochemical (oil and gas) concessions and infrastructure and mineral or aggregate extraction sites. Fine-scale information on offshore vessel movements, such as shipping, however, is often lacking from MSP (McCauley et al., 2016). Consequently, the availability of spatial information on the movement of maritime vessels and potential impact across marine ecosystems, habitats and ocean user-groups that can be included in MSP processes lags well behind what is required to effectively inform decision-making. Here, using examples from Congo-Brazzaville, we outline five key reasons why the analysis of publicly accessible S-AIS data can improve our understanding of shipping and fill gaps in ocean

observation data, thereby increasing transparency and ensuring that all sectors are represented in decision-making processes.

First, S-AIS data provide detailed information on the different types and number of vessels that operate from the coast out to the limits of an EEZ (i.e. 200 nautical miles) that can be used to identify the range of stakeholder groups that should be engaged in decision-making processes. For example, this study revealed that, of the 10 vessel categories that operate in Congo-Brazzaville (Table 1), maritime traffic is dominated by commercial vessels (bulk carrier and cargo vessels and tankers) and vessels involved in servicing the offshore petrochemical industry (offshore service and passenger vessels), with these sectors accounting for 93.7% of the total number of unique vessels and traffic annually. These findings thus reinforce the importance of the petrochemical sector and associated support services to the local and national economy.

Second, S-AIS data can be used to derive a range of fine-scale data layers that reveal the true extent of vessel activity beyond the range of conventional AIS which is typically limited to territorial waters. For example, this study shows that shipping dominates ocean use with the four major vessel categories (passenger vessels, offshore service vessels, bulk carrier and cargo vessels and tankers) operating within a combined area equivalent to 92.0% of Congo-Brazzaville's

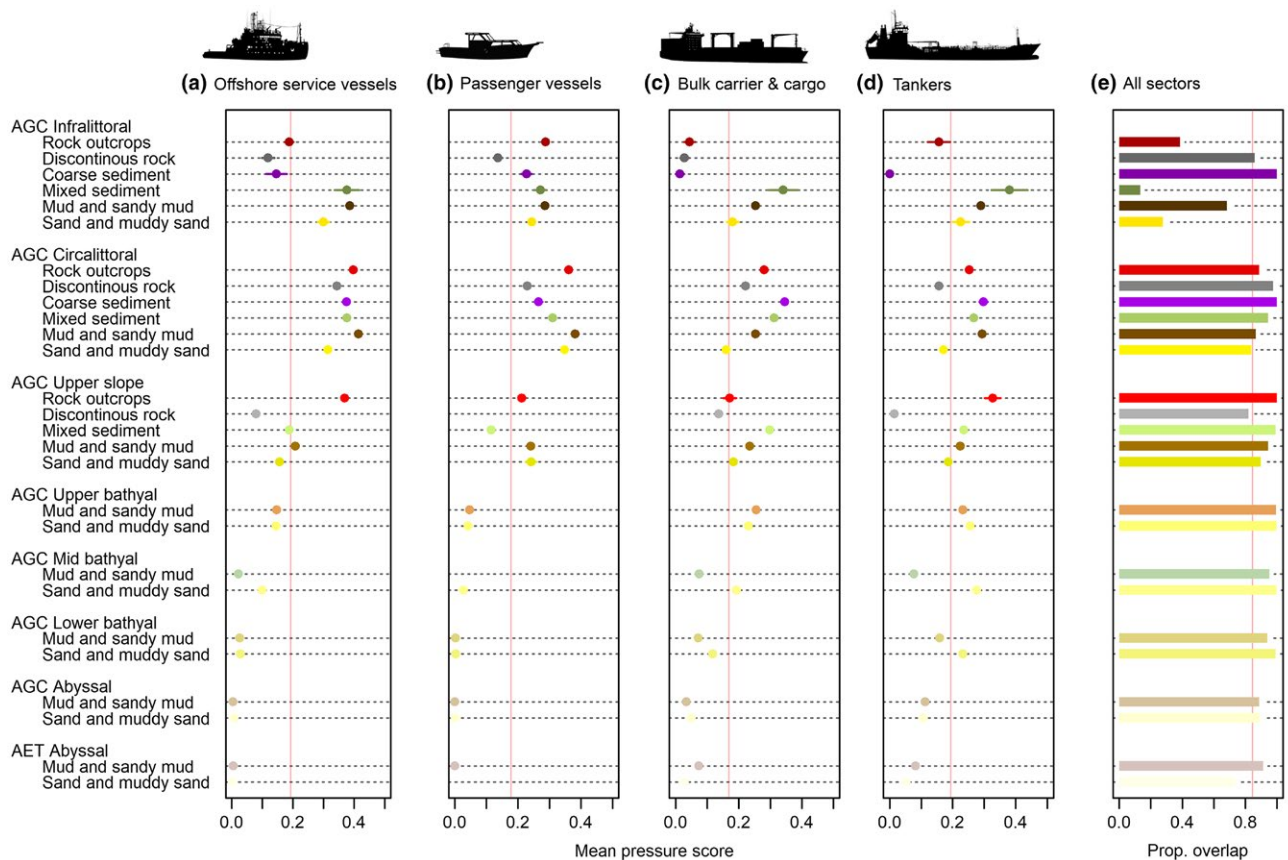


FIGURE 5 Mean vessel pressure score for each habitat type for: (a) offshore service vessels; (b) passenger vessels; (c) bulk carrier and cargo vessels; (d) tankers; and (e) the proportion of each habitat subject to vessel pressure. Habitat labels: AGC, Atlantic Guinea Current; AET, Atlantic eastern tropical. For each panel, the solid red line indicates the mean of values for each habitat type [Colour figure can be viewed at wileyonlinelibrary.com]

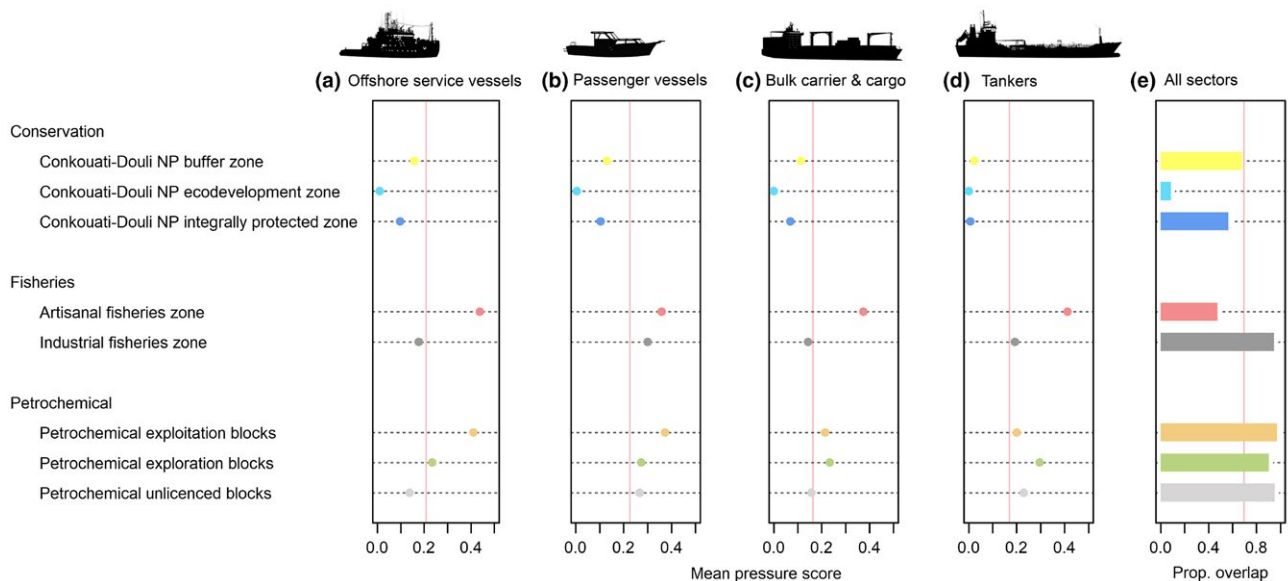
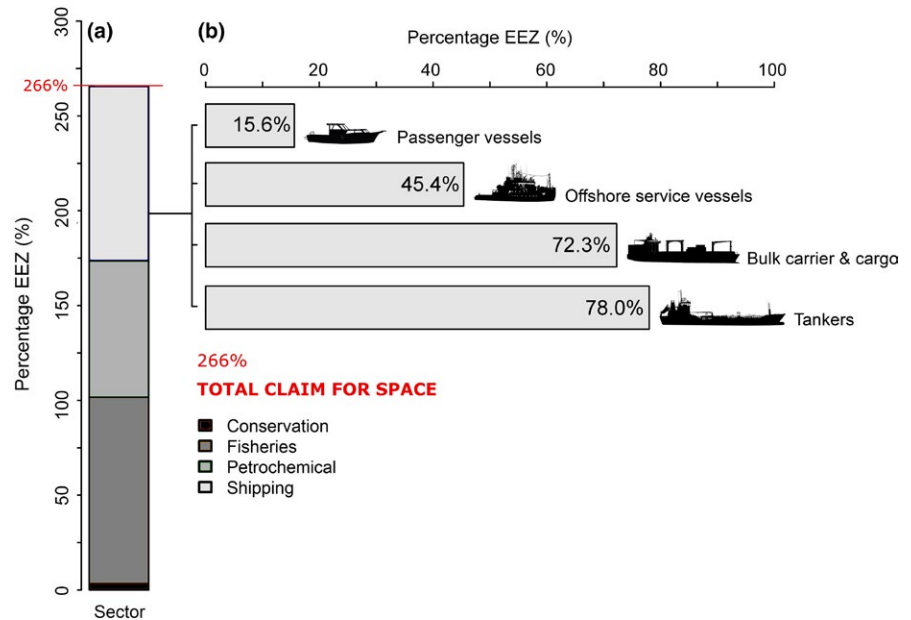


FIGURE 6 Mean vessel pressure score for each zone for: (a) offshore service vessels; (b) passenger vessels; (c) bulk carrier and cargo vessels; (d) tankers; and (e) the proportion of each zone subject to vessel pressure. For each panel, the solid red line indicates the mean of values for each zone [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 7 Estimates of (a) the total amount of Congo-Brazzaville's EEZ claimed (based on legislation) for ocean-based activities such as conservation (national designations), fisheries (artisanal and industrial fishing zones), petrochemical extraction (concession blocks), including combined maritime shipping footprint and (b) the individual spatial footprint for passenger vessels, offshore service vessels, bulk carrier and cargo vessels and tankers [Colour figure can be viewed at wileyonlinelibrary.com]



EEZ (Figure 7). This far exceeds the areas allocated for, and used by other human uses such as conservation areas, fisheries zones and petrochemical concessions (Figure 7).

Third, S-AIS can help visualise patterns of vessel behaviour such as intensity and occupancy to highlight areas that are consistently utilised in time and space. For example, whilst there is variation in the size of spatial footprint among sectors operating in Congo-Brazzaville (Figure 7), the majority of vessel transits occur within distinct shipping routes. More specifically, the study shows that for commercial vessels such as bulk carrier and cargo vessels and tankers, the area associated with the greatest activity is around the shipping routes that are used to access the port city of Pointe Noire. For offshore and passenger vessels, the areas associated with the greatest activity are most evident around petrochemical infrastructure. Given that, most policy and management actions are targeted at modifying human behaviours failure to understand these sectoral differences could reduce the effectiveness of proposed measures and/or compliance with new regulations, especially considering shipping from ports must use fixed access areas, whereas offshore shipping routes are not fixed, and therefore can be rerouted (Wiley, Hatch, Schwehr, Thompson, & MacDonald, 2013).

Fourth, S-AIS data can be used to develop putative threat maps that identify how different vessel types and their associated pressures overlap with marine ecosystems, habitats and species (subject to data availability). For example, Congo-Brazzaville's continental shelf is an important breeding, foraging, nesting and migratory area for several globally important and threatened populations of marine mammals and sea turtles (Metcalf et al., 2015; Pikesley et al., 2013; Rosenbaum et al., 2014; Weir & Collins, 2015); prior to this study, it was assumed that the greatest threat to these groups was from fisheries. However, the findings of this study highlight that the shallow water habitats of Congo-Brazzaville's continental shelf (particularly those outside of existing conservation areas) are where pressure from maritime traffic is greatest. Such information is essential to

help develop targeted mitigation measures that can include implementing vessel speed regulations and/or rerouting shipping lanes to reduce exposure to negative impacts that can disrupt ecosystems and natural behaviours (Coomber et al., 2016; Dransfield et al., 2014). Furthermore, identifying "quiet(er)" and "noisy" ocean areas and assessing potential for ship strike are considered among the key priorities when developing marine spatial plans in regions that incorporate the range of mobile marine vertebrates (Parsons et al., 2015; Redfern et al., 2013; Williams, Erbe, Ashe, & Clark, 2015). However, this would require seasonally explicit maps of vessel activity to investigate the potential for species-specific interactions (McKenna, Calambokidis, Oleson, Laist, & Goldbogen, 2015).

Fifth, static visualisations of the spatiotemporal distribution of shipping activity can also identify current levels of overlap with areas allocated to other human uses. Such information provides an important baseline from which practitioners can explore multiple scenarios and assess trade-offs associated with proposed zoning and management measures. For example, here we show that the greatest overlap between shipping and other human uses is with fisheries more than that for conservation or petrochemicals. This is because many of the vessels associated with shipping in Congo-Brazzaville are linked to the petrochemical sector and hence are required to pass through the artisanal and industrial fishing zones to access petrochemical infrastructure, or the port city of Pointe Noire, thereby reducing available fishing area. Consequently, marine spatial plans that place further pressure on available fishing areas, particularly artisanal fisheries, could lead to negative impacts on local livelihoods.

5 | CONCLUSIONS

Due to the economic efficiency of shipping as a mode of transport as well as the volume and distance over which material is transported, the global fleet (in terms of deadweight tonnage) and

average size of container ships has increased 41.6% and 18.2%, respectively, between 2010 and 2015 (UNCTAD, 2016) and are projected to increase further over the next decade (Kaplan & Solomon, 2016). Evolving industries are also expanding markets for certain products and commodities (e.g. liquefied natural gas, iron ore and potash), and hence, the development of new port facilities is increasing, particularly in developing nations where data are few but development proceeds apace with “best practice” (Robards et al., 2016). As a consequence, there is an urgent need to identify potential conflicts between shipping and marine ecosystems, habitats and other ocean-based activities and user groups. Here, we have shown how S-AIS offers a cost effective solution for practitioners to address current knowledge gaps by providing high-quality data over a larger area than conventional AIS; which can subsequently be used to derive a range of fine-scale data and threat layers that can help support more effective decision-making processes in relation to EBM and MSP.

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AUTHORS' CONTRIBUTIONS

K.M., B.J.G. and M.J.W. conceived the idea and analysed the data; K.M., T.C., B.J.G., R.J.P., R.A.T. and M.J.W. contributed to interpretation of the results; and all co-authors K.M., N.B., E.C., T.C., B.K.C., B.J.G., R.J.P., R.A.T. and M.J.W. contributed to writing the paper and gave final approval for publication.

DATA ACCESSIBILITY

All raw automatic identification system (AIS) data used in this study are archived by and can be obtained under commercial licence from © 2018 exactEarth Ltd. All Rights Reserved: <https://www.exactearth.com/>.

Derived raster products (intensity, occupancy and pressure) and spatial data layers describing marine boundaries, habitats, ecosystems and legal zoning designations available from the Dryad Digital Repository <https://doi.org/10.5061/dryad.6373nd6> (Metcalf et al., 2018).

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