

## LETTER

# Addressing Uncertainty in Marine Resource Management; Combining Community Engagement and Tracking Technology to Characterize Human Behavior

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## Abstract

Small-scale fisheries provide an essential source of food and employment for coastal communities, yet the availability of detailed information on the spatiotemporal distribution of fishing effort to support resource management at a country level is scarce. Here, using a national-scale study in the Republic of Congo, we engaged with fishers from 23 of 28 small-scale fisheries landing sites along the coast to demonstrate how combining community engagement and relatively low cost Global Positioning System (GPS) trackers can rapidly provide fine-scale information on: (1) the behavioral dynamics of the fishers and fleets that operate within this sector; and (2) the location, size and attributes of important fishing grounds upon which communities are dependent. This multidisciplinary approach should be considered within a global context where uncertainty over the behavior of marine and terrestrial resource-users can lead to management decisions that potentially compromise local livelihoods, conservation, and resource sustainability goals.

## Introduction

Globally, small-scale fisheries employ 22 million of the 50 million people engaged in fishing worldwide (Teh & Sumaila 2013), and so make an important contribution to many local and national economies due to their essential role in food security, employment, and poverty alleviation (Béné 2006). However, while there is increasing information that describes small-scale fisheries

catches (Pauly & Zeller 2016), detailed information on the spatiotemporal distribution of their effort at a country level is scarce, particularly in developing countries (Chuenpagdee *et al.* 2006). Whilst some data exist, their use is often limited by the absence of systematic data collection arising from: (1) limited financial, personnel and/or technical resources; (2) the dispersed nature of fishing communities; and (3) insufficient licensing or monitoring (Stewart *et al.* 2010). This ultimately

leads to poor management decisions, which can in turn affect employment and standards of living in fisheries dependent-communities, particularly where there are few alternative livelihood opportunities (Pomeroy and Andrew 2011). For instance, the underestimation of fleet size and effort can lead to overexploited fisheries and increased bycatch, particularly as fishers adapt, and expand their effort to overcome declining catches (Weeratunge *et al.* 2014; Belhabib *et al.* 2015). In addition, a lack of useable data can create challenges in securing fishers' access rights to important fishing grounds (FAO 2014), which can lead to conflict between fishers and government agencies or other resource users over competing demands for space (DuBois & Zografos 2012).

Different disciplines offer different solutions to these issues; fisheries scientists argue for a combination of input and output controls to address overfishing, sociologists for community- or rights-based management to protect access to important fishing grounds, and ecologists and conservationists for ecosystem-based management to balance competing uses (Branch *et al.* 2006; Degnbol *et al.* 2006). Nonetheless, the successful implementation of any, or a combination of these strategies requires an understanding of how individual fishers and fleets behave (Branch *et al.* 2006; Hilborn 2007; Fulton *et al.* 2011). Creating an evidence base on small-scale fisheries behavior, however, is likely to be more challenging than for industrial fleets, which are often subject to monitoring and control through vessel monitoring systems (Witt & Godley 2007). Beyond active recording of vessel sightings by enforcement agencies, existing approaches to map small-scale fisheries have largely been based on extrapolations of behavioral rules, such as how far fishers travel, or rely on interview data, both of which have their limitations (Breen *et al.* 2015; Turner *et al.* 2015). For example, behavioral rules assume that the behavior of fishers is uniform (Dunn *et al.* 2010; Stewart *et al.* 2010). Interviews, on the other hand, are resource intensive, reliant on fishers' participation, and can vary in accuracy due to differences in fishers' spatial perceptions (Yates & Schoeman 2013; Turner *et al.* 2015). Consequently, these approaches do not always accurately describe fishers behaviors, and are often limited to a few study sites (Teh & Teh 2011).

Fortunately, the last decade has seen an increase in cost-effective technologies suitable for characterizing the behavior of resource users (Alvard *et al.* 2015; Papworth *et al.* 2012). Here, using a national-scale study in the Republic of Congo, we demonstrate how Global Positioning System (GPS) trackers can be used by fishing communities to collect fine-scale information to facilitate more effective resource management decisions. More specifically, we show how trackers can be used to identify

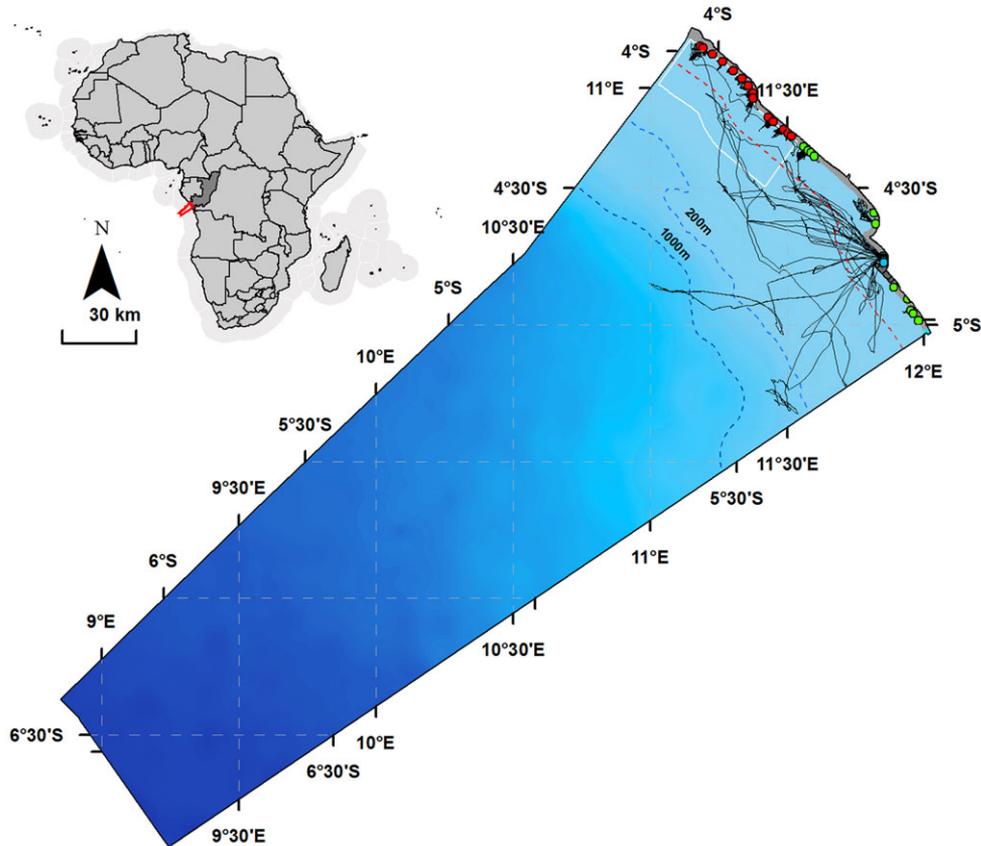
variation in fisher behavior, and the spatiotemporal distribution of fishing effort. In the Republic of Congo, this sector employs ~2,600 fishers, which together with ~35,300 dependents and ~26,900 workers not directly engaged in fishing (e.g. processing and marketing), supports around ~9% of the coastal population (Belhabib *et al.* 2015). However, despite its importance to fisheries-dependent households (Brugère *et al.* 2008), small-scale fisheries are under pressure from overexploitation, industrial and illegal trawl fisheries, offshore petrochemical exploitation, and calls for increased marine protection (Belhabib & Pauly 2015). These data will thus enable planners, managers, and decision makers (hereafter practitioners) to better reflect stakeholder priorities and account for actual patterns of resource use in decision-making. Ultimately, the adoption of tracking technology could reduce inconsistencies in the availability of data across the different sectors operating in this region, thereby contributing to a more accurate representation of the small-scale fisheries sector in later policy, planning and resource management decisions.

## Methods

### Characterizing behavior

Small-scale fisheries in the Republic of Congo (Figure 1) are defined as motorized and nonmotorized vessels that require the use of manual labor (e.g., hand-hauling; Figure 2) during fishing operations (Loi No 2 2000). Under existing regulations all waters within six nautical miles of the coast are reserved for small-scale fisheries, equivalent to 4.6% of the Republic of Congo's Exclusive Economic Zone. However, poor enforcement means that industrial vessels are regularly observed and/or apprehended operating illegally within this zone (Bal *et al.* 2007; Figure 2).

Between February 2014 and March 2015, GPS trackers with motion sensors that detect when the unit is moving and/or stationary were deployed on 41 vessels across 23 of the 28 small-scale fisheries landing sites that operate along the national coast (Figure S1). Devices were programmed to acquire GPS locations at 5-minute intervals and carried on board by fishers. Once each GPS unit was retrieved we removed pre- and postdeployment locations (associated with travel to and from the landing sites), and GPS locations that were not associated with fishing trips. We defined the beginning of a trip from the first two consecutive GPS locations once in motion, and excluded locations at the end of each trip after two or more consecutively missed positions once fishers returned to land, thus indicating that the unit was stationary (see Methods S1 for a description of GPS unit configuration,



**Figure 1** Small-scale fisheries landing sites ( $n = 28$ ) and movements at sea (solid black lines) derived from GPS-based trackers deployed at 23 landing sites situated along the national coast of the Republic of Congo. Dashed red line indicates the limit of the zone reserved exclusively for artisanal fisheries and dashed blue lines indicates the 200 and 1,000 m bathymetric contours. Landing sites classified as follows: (Zone A) inside the National Park (red filled circles,  $n = 12$  sites); (Zone B) outside the National Park and city of Pointe Noire (green filled circles,  $n = 11$  sites); and (Zone C) inside the city of Pointe Noire (blue filled circles,  $n = 5$  sites).

deployment methodology, and summary of sampling effort). To ensure that the track log data were standardized to 5-minute intervals, we used the *approx* function in R (R Core Team 2014) to linearly interpolate missing GPS locations resulting from signal loss (mean proportion of locations interpolated per trip:  $0.2 \pm 0.2$  CI: 0.19–0.26;  $n = 875$  trips). To characterize the behavior of fishers operating in this sector we calculated seven behavioral metrics associated with each trip: (1) total duration (hours), (2) total distance traveled (km), (3) maximum displacement distance (km), (4) maximum offshore distance (km), (5) average speed (km/h), (6) maximum depth (meters) and (7) spatial footprint ( $\text{km}^2$ ; Methods S2). In addition, we recorded the number of boats operating from each landing site using data provided by local fisheries representatives.

To determine whether fisher behavior varied among locations, we assigned landing sites to one of three groups

(Table 1; Figure 1) according to differences in existing management regulations, local population density, available resources (number of boats and access to engines) and proximity to major markets as follows: “Zone A” inside Conkouati–Douli National Park ( $n = 12$  sites;  $n = 20$  boats;  $n = 684$  trips); “Zone B” outside the National Park and city of Pointe Noire ( $n = 8$  sites;  $n = 14$  boats;  $n = 169$  trips); and “Zone C” inside the city of Pointe Noire ( $n = 3$  sites;  $n = 7$  boats;  $n = 22$  trips). Sample accumulation curves indicated that sampling effort was sufficient to identify the limits within which fishers from each zone operated (Methods S3). Generalized linear mixed-effects models were used to examine the variation among these three groupings on the seven behavioral metrics using the *nlme* package in R (Pinheiro *et al.* 2015). To control for site specific differences and multiple trips per fisher, Landing Site and Fisher ID were included as nested random effects. Models were fitted with a Gaussian error



**Figure 2** Typical fishing fleets active in the Republic of Congo: (I) small-scale nonmotorized boats observed operating from landing sites outside the city of Pointe Noire (Zones A and B); (II) small-scale (semi-industrial) motorized fishing boats observed operating from landing sites inside the city of Pointe Noire (Zone C); and (III) industrial and illegal industrial trawl fisheries (vessel photographed was apprehended trawling within the artisanal fishing zone in Conkouati-Douli National Park). Photo credits: (I) Kristian Metcalfe (University of Exeter), (II and III) Tim Collins (Wildlife Conservation Society).

distribution and checked for normality and heteroscedasticity. All response variables were log-transformed to ensure normality of residuals, and *post hoc* Tukey tests were undertaken to test the significance of among group differences using the *multcomp* package in R (Hothorn *et al.* 2015).

### Mapping fisheries activity

To describe the spatiotemporal patterns of fisheries activity we report the number of boats operating per unit area (25 km<sup>2</sup> hexagons). This approach was used to describe the distribution of fleet activity (i.e., occupancy), and involved calculating the number of boats operating in each grid cell from each landing site. These occupancy metrics were then scaled to account for vessels that were not tracked, assuming that, on average, additional vessels

would behave in the same way as those tracked from the same landing site, as only one major gear type is used in each zone (Table 1). This was then repeated for all sites and summed, resulting in an inferential zone of influence for small-scale fisheries. To account for differences in fisher behavior among sites we scaled the number of boats in each cell by the mean number of hours recorded per trip per unit area, providing an initial indication of important locations that is potentially analogous to fishing pressure. To illustrate the relative differences in the distribution and scale of fishing activity along the coast we undertook these analyses separately for fishers operating from sites outside the city of Pointe Noire (Zones A and B;  $n = 20$  sites), and fishers operating from sites inside the city of Pointe Noire (Zone C;  $n = 3$  sites) due to their different modes of operation (Figure 2).

### Results

Field surveys recorded a total of 689 boats that operated from the 28 landing sites: 26 inside the National Park (Zone A; 4%), 126 outside the National Park and city of Pointe Noire (Zone B; 18%), and 537 inside the city of Pointe Noire (Zone C; 78%). All boats in Zones A and B were wooden pirogues, whereas those in Zone C were comprised of a mixture of large fiberglass and/or wooden pirogues with outboard engines.

Although the behavior of fishers across the majority of landing sites were similar, the data revealed striking differences (Figure 3) that were linked to where fishers were based (GLMM,  $P < 0.001$ ; Table S1; Figure S2). For example, city fishers (Zone C) tended to conduct fishing trips that were on average  $>10$  times longer in duration and further in distance than fishers from elsewhere (Zones A and B) (all  $P < 0.001$ ; Tables S1 and S2; Figure S2). There were no significant differences in the measures of behavior among fishers outside the city (Zones A and B;  $P > 0.074$ ; Table S1; Figure S2); with fishers from these sites operating over similarly small spatiotemporal scales (Table S2). Further analysis of the attributes of important fishing grounds also revealed that fishers outside the city (Zones A and B) tended to concentrate their effort in shallow coastal waters, whereas city fishers (Zone C) concentrated their effort in deeper waters further offshore (Figure 4; Table S2).

In addition, whilst there was some overlap in fishing effort among groups, city fishers (Zone C) typically operated beyond the limits of the artisanal fisheries zone (Figure 5) within a footprint  $>190$  times larger than fishers from elsewhere (Zones A and B;  $P < 0.001$ ; Table S1; Figure S3). There were no significant differences in the size of spatial footprint among fishers operating outside the city (Zones A and B;  $P = 0.858$ ; Table S1; Figure S3);

**Table 1** Differences in the characteristics of the 28 small-scale fisheries landing sites situated along the national coast of the Republic of Congo. Each group is defined as follows: (Zone A) inside the National Park ( $n = 12$  sites); (Zone B) outside the National Park and city of Pointe Noire ( $n = 8$  sites); and (Zone C) inside the city of Pointe Noire ( $n = 3$  sites)

Characteristics	Zone A	Zone B	Zone C
Number of landing sites (percentage tracked)	12 (100%)	11 (73%)	5 (60%)
Population within a 10 km radius of landing sites <sup>a</sup>	Range: 407–1,513 Mean: 1,124 ± 418	Range: 1,452–5,197 Mean: 3,270 ± 1,308	Range: 654,058–695,494 Mean: 677,438 ± 17,739
Distance to largest fish market (km)	Range: 64–115 km Mean: 89 ± 18 km	Range: 11–57 km Mean: 32 ± 18 km	Range: 0.4–3 km Mean: 2 ± 1 km
Total number of boats	Range: 1–3 Mean: 2 ± 1	Range: 3–57 Mean: 11 ± 16	Range: 4–507 Mean: 107 ± 223
Number of sites with engines	0 (0%)	1 (11%)	5 (100%)
Monitoring/enforcement organizations	National Park	Fisheries agency	Fisheries agency
Nationality of fishers	Congolese	Congolese	West African (e.g., Benin, Ghana, Nigeria, Senegal)
Primary fishing gear	Static set gill nets	Static set gill nets	Drift/static set gill nets

<sup>a</sup>Population density estimates are based on the sum of population within a 10-km radius of each landing site derived from LandScan 2012 Global Population Database (Oak Ridge National Laboratory 2012).

fishers from these sites operated exclusively within the artisanal fishing zone in areas that were on average <3 km<sup>2</sup> (Table S2).

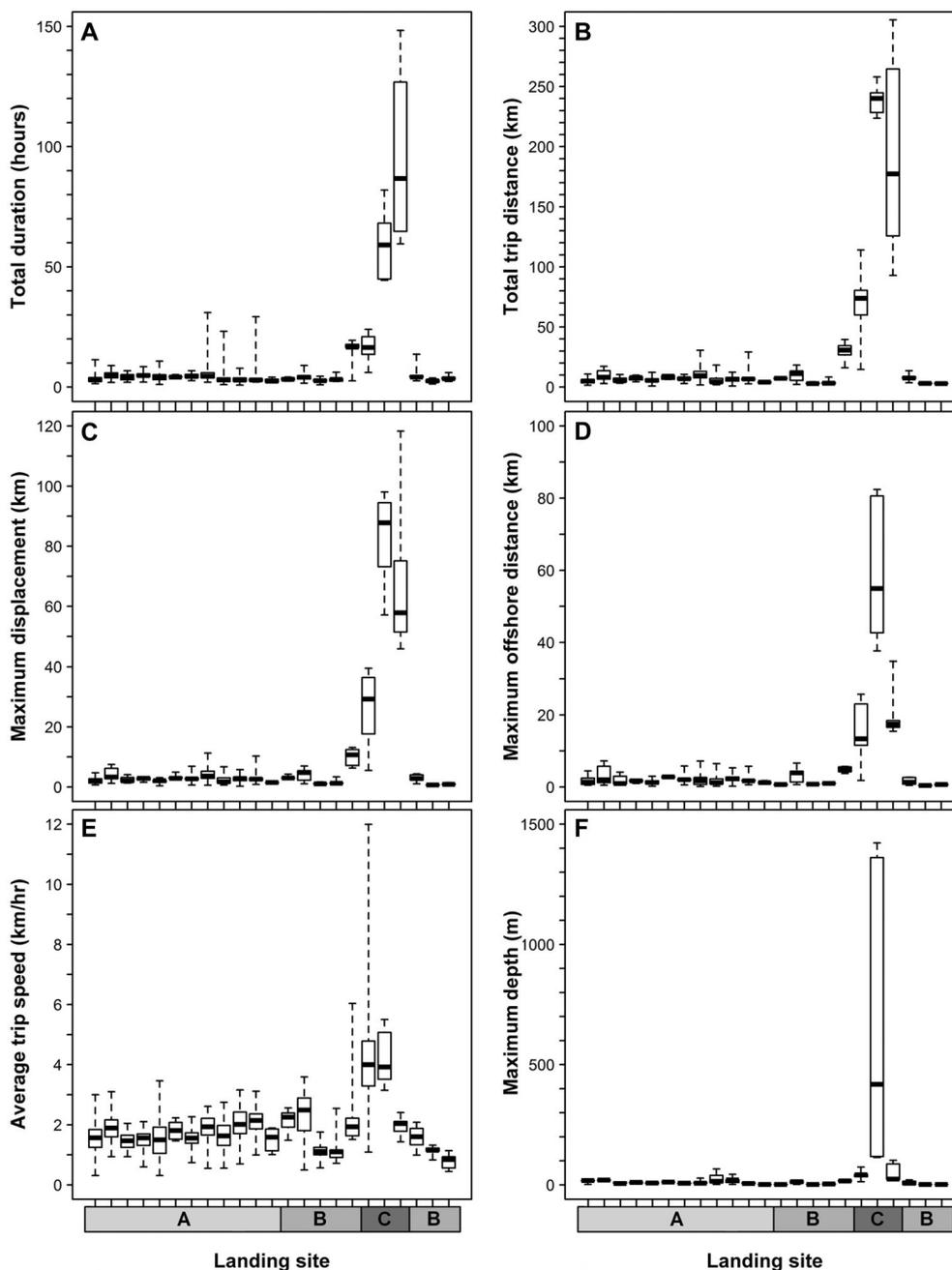
## Discussion

Despite, small-scale fisheries contributing to the livelihoods and well-being of 10% of the world's population (FAO 2014), traditional approaches to marine resource management are failing to address overfishing, protect access to important fishing grounds and balance competing uses, as there is often a poor understanding of how fishers interact with the marine environment (Fulton *et al.* 2011; Kittinger *et al.* 2014). Here we show how linking well-established techniques from the social sciences (community engagement and participatory data collection) with technologies traditionally employed in the natural sciences (GPS tracking) can provide much-needed fine-scale information on the behavioral dynamics of the small-scale fisheries sector.

In the context of the Republic of Congo, we reveal that there are two distinct types of fisheries fleets. These are: (1) small wooden pirogues operated by hand, traditionally employed by Congolese fishers outside of the city and (2) large fiberglass and/or wooden pirogues equipped with (25–40 hp) outboard engines typically employed by West African fishers in the city (Figure 2). The former are more typical of an artisanal or subsistence based fishery with fishers dependent on undertaking daily fishing trips within shallow coastal waters. The latter, however, are more analogous to a semi-industrial fishery, with fishers

operating for extended periods over vast areas in deeper waters further offshore. Failure to understand the differences in the opportunities and constraints that shape these behaviors (e.g., geographical isolation and available resources) could reduce the effectiveness of proposed management strategies. For instance, fishers outside the city operate within a relatively informal sector, with lack of investment in infrastructure (e.g., ice making and storage facilities) and resources due to: (1) a small surrounding population, and therefore limited market; (2) a lower market value for their catch, as salted and/or smoked fish is less valuable than fresh fish; and (3) high costs associated with transporting catch to markets in the city, both in time not spent fishing and financial resources. Consequently, these communities are unable to invest in equipment that will allow them to exploit areas further offshore. Therefore, any actions that place increasing constraints on these less mobile fishing communities that are dependent on areas <3 km<sup>2</sup>, could have a far greater socioeconomic impact on livelihoods and food-security, compared to city fishers that are likely to be more resilient due to: (1) the motorized nature of their fishery, which allows them to operate over areas >500 km<sup>2</sup> and (2) access to an expanding urban population who rely on fish as an important source of protein (Béné & Heck 2005).

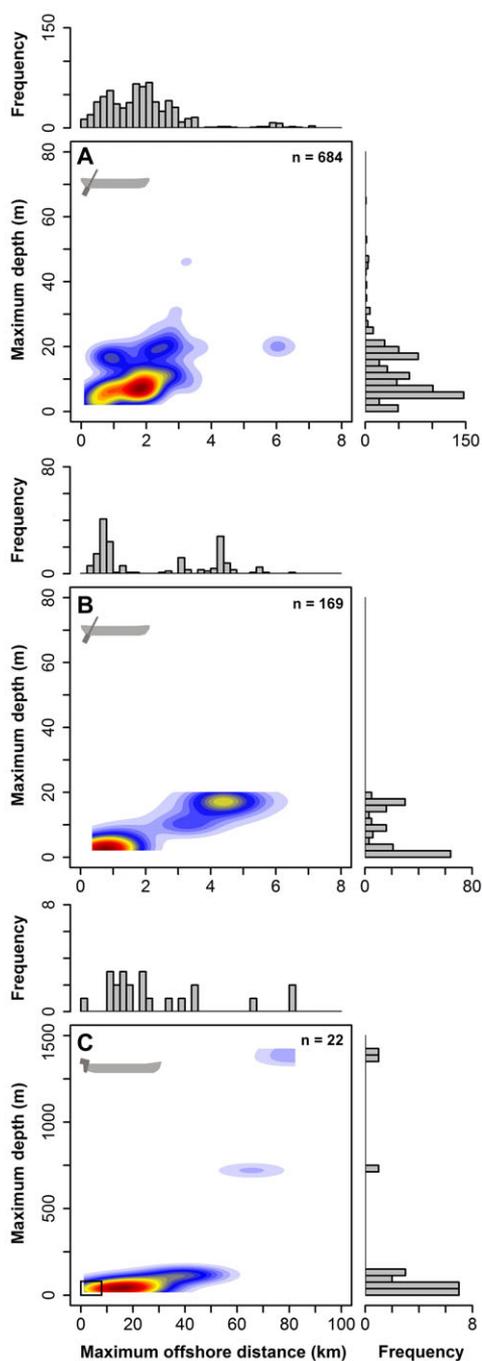
Given that most policy and management actions in marine ecosystems are targeted at human activities, a detailed understanding of fishers' behaviors, such as that described here, is essential as it provides a better understanding of the complex linkages between people



**Figure 3** Small-scale fishers operating behavior derived from GPS trackers deployed at 23 surveyed landing sites situated along the national coast of the Republic of Congo. Boxplots depict the 25th, 50th (median), and 75th percentiles, with whiskers extended to show the minimum and maximum of all trip data for each landing site. To allow visual comparisons between differences in the operating behavior the 23 landing sites are ordered per their latitudinal distribution along the coast, from the border with Gabon in the North to Cabinda in the South (see Figure 1).

and the environment (Fulton *et al.* 2011). In terms of fisheries management, behavior data can reveal the spatiotemporal distribution of fishing effort—which grounds are heavily fished and which are not convey important information about local stocks. Consequently, these data

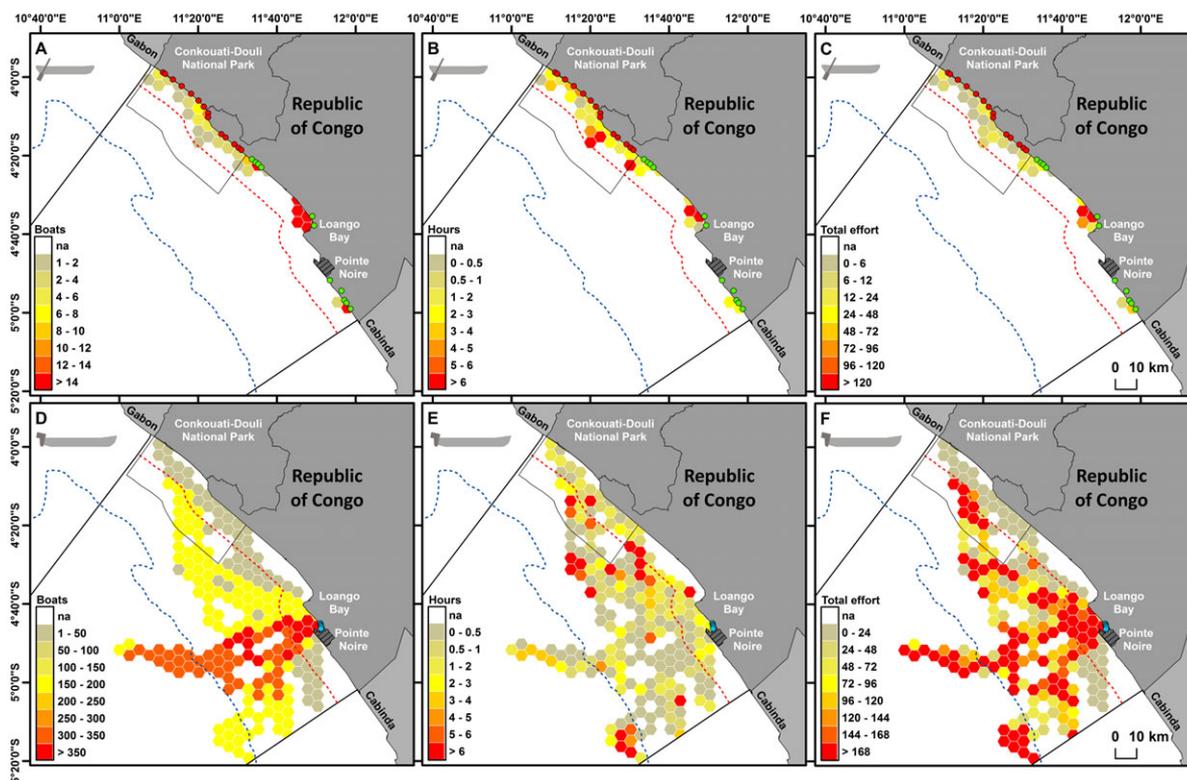
can be used to implement closed periods or measures to control overexploitation, such as restrictions on the number of fishing days, gear types and engine power (to limit catches and reduce bycatch). Moreover, these data provide a baseline from which practitioners can evaluate



**Figure 4** Location and attributes of small-scale fisheries effort distribution derived from GPS trackers deployed from landing sites located in Zone A, inside the National Park ( $n = 12$  sites;  $n = 684$  trips); Zone B, outside the National Park and city of Pointe Noire ( $n = 8$  sites;  $n = 169$  trips); and Zone C, inside the city of Pointe Noire ( $n = 3$  sites;  $n = 22$  trips). To highlight variation in the maximum offshore distance and depth associated with fishing trips we calculated kernel density estimates for each group, which results in a utilization distribution that describes areas of high use (red) and low use (blue). Marginal histograms highlight the distribution of raw distance and depth data for each group. For comparative purposes the black inset in plot (C) highlights the range of plots (A) and (B).

the impact of new regulations on behavior change, such as effort displacement and compliance. With regard to community- or rights-based management, behavior data can enable better social outcomes for fisheries management and planning initiatives (Ban *et al.* 2013). This is because it reveals fine-scale variation in the mobility of individual fishers, which can influence the location, size and attributes (i.e. spatial preferences) of important fishing grounds that communities are dependent upon for their livelihoods and food security. In the context of fisheries- and ecosystem-based management, these preferences can be explicitly quantified and mapped to reveal how fishers interact with the marine environment, identify conflict between other user groups or ecologically sensitive areas, and assess the trade-offs associated with potential changes. This also facilitates their inclusion in decision support tools now prevalent in marine spatial planning, where spatial data on how people use resources can be represented as threats to biodiversity, or costs associated with management actions (Ban & Klein 2009). For example, where fishing activities represent a threat to biodiversity, practitioners can either avoid these areas to minimize conflict, or prioritize these areas to reduce pressures on biodiversity. Costs, on the other hand, can relate to damage to economic activities arising from the loss of extractive opportunities (Ban *et al.* 2013). Thus, where competing development demands or conservation priorities overlap with important fishing grounds, practitioners can minimize opportunity costs and therefore impacts on local livelihoods by avoiding excluding fishers from areas with high levels of fishing effort (Ban & Klein 2009). Fishers' increasingly want to have a greater say in management and we detail one such approach that can provide them with a voice. Transferring the knowledge of fishers' behaviors to science and management can, however, present a number of ethical challenges that can have damaging outcomes for communities; especially where data is presented in the form of maps that can be easily accessed by other fisheries sectors or user groups (Maurstad 2002; Jentoft & Knol 2014). With this in mind and in agreement with fishers we present effort maps at a coarse scale so as not to compromise the exact location of important fishing grounds.

Globally, existing approaches to marine and terrestrial resource management often fail to achieve a broad range of biological, economic and social objectives due to uncertainty over the behavior of resource-users, or as a result of resource-dependent communities being marginalized from decision making processes. By generating detailed information on the behavior of individuals, the multi-disciplinary approach detailed herein can help promote more effective management strategies that account for patterns of resource use in decision making processes.



**Figure 5** Spatial distribution of fisheries activity and effort for fishers operating from landing sites outside the city (Zones A and B:  $n = 20$  sites; A–C) and inside the coastal city of Pointe Noire Zone C:  $n = 3$  sites; D–F). Spatial distribution of (A, D) fleet activity (number of boats per unit area); (B, E) mean number of hours per trip per unit area; and (C, F) fishing pressure per unit area. Dashed red line indicates the limit of the zone reserved exclusively for artisanal fisheries and the dashed blue line indicates the 200 m depth contour. Landing sites are classified as follows: Zone A: red circles ( $n = 12$  sites); Zone B: green circles ( $n = 8$  sites); and Zone C: blue circles ( $n = 3$  sites).

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## Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher’s web site:

**Methods S1.** Detailed description of GPS unit configuration, deployment methodology, and summary of sampling effort.

**Methods S2.** Methods used to calculate the total duration, total distance traveled, maximum displacement distance, maximum offshore distance, average speed,

maximum depth and spatial footprint associated with each individual fishing trip.

**Methods S3.** Methods used to assess the amount of new information gained by each additional trip within each zone.

**Table S1.** The effect of group on measures of fishers operating behavior tested using generalized linear mixed-effect models.

**Table S2.** Small-scale fisheries behavioral characteristics derived from the GPS trackers and summarized for landing sites situated inside the National Park (Zone A), outside the National Park and city of Pointe Noire (Zone B), and inside the city of Pointe Noire (Zone C).

**Figure S1.** Date of first GPS deployment at each of the 23 surveyed landing sites which participated in the study.

**Figure S2.** Small-scale fishers operating behavior derived from trips associated with landing sites situated inside the National Park (Zone A), outside the National Park and city of Pointe Noire (Zone B), and inside the city of Pointe Noire (Zone C).

**Figure S3.** Variation in the spatial footprint associated with each fishing trip from each landing site and landing sites situated inside the National Park (Zone A), outside the National Park and city of Pointe Noire (Zone B), and inside the city of Pointe Noire (Zone C).

**Figure S4.** Sample accumulation curves illustrating the amount of new information about the attributes of important fishing locations (displacement, offshore distance and depth) gained by each additional trip, within each zone.

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