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Remote electronic monitoring as a potential alternative to on-board observers in small-scale fisheries☆

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ABSTRACT

Small-scale fisheries can greatly impact threatened marine fauna. Peru's small-scale elasmobranch gillnet fishery captures thousands of sharks and rays each year, and incidentally captures sea turtles, marine mammals and seabirds. We assessed the ability of a dedicated fisheries remote electronic monitoring (REM) camera to identify and quantify captures in this fishery by comparing its performance to on-board observer reports. Cameras were installed across five boats with a total of 228 fishing sets monitored. Of these, 169 sets also had on-board fisheries observers present. The cameras were shown to be an effective tool for identifying catch, with > 90% detection rates for 9 of 12 species of elasmobranchs caught. Detection rates of incidental catch were more variable (sea turtle = 50%; cetacean = 80%; pinniped = 100%). The ability to quantify target catch from camera imagery degraded for fish quantities exceeding 15 individuals. Cameras were more effective at quantifying rays than sharks for small catch quantities ($x \le 15$ fish), whereas size affected camera performance for large catches ($x > 15$ fish). Our study showed REM to be effective in detecting and quantifying elasmobranch target catch and pinniped bycatch in Peru's small-scale fishery, but not, without modification, in detecting and quantifying sea turtle and cetacean bycatch. We showed REM can provide a time- and cost-effective method to monitor target catch in small-scale fisheries and can be used to overcome some deficiencies in observer reports. With modifications to the camera specifications, we expect performance to improve for all target catch and bycatch species.

1. Introduction

Overexploitation has long been identified as a major threat to global biodiversity (Diamond, 1984), especially in the marine biome (Knapp et al., 2017). Monitoring of biodiversity and exploitative activities has been identified as a major priority in conservation biology (Bawa and Menon, 1997) and new monitoring tools are being developed for a variety of biomes (e.g. Bicknell et al., 2016; Rist et al., 2010). Improved monitoring of the fisheries sector is of particular importance as global illegal, unreported and unregulated (IUU) fishing practices are estimated at 11–26 million tonnes per annum (Agnew et al., 2009).

Small-scale fisheries make a substantial contribution to global fish captures (Chuenpagdee et al., 2006), producing more than half of the world's annual catch and supplying most fish consumed in developing nations (Berkes et al., 2001). However, despite their importance to global catches, small-scale fisheries are often largely under-regulated (Berkes et al., 2001). Moreover, small-scale fisheries remain relatively unstudied compared to large industrial fisheries due to insufficient resources and poor infrastructure (Berkes et al., 2001; Lewison et al., 2004; Mohammed, 2003; Pauly, 2006), making it difficult to quantify their impacts on target and non-target species (Berkes et al., 2001; Lewison et al., 2004; Pauly, 2006).

Independent on-board observers have traditionally been used to monitor target catch (Alfaro-Cordova et al., 2017; Haigh et al., 2002; Mangel et al., 2013) and bycatch (Caretta et al., 2004; Gales et al., 1998; Rogan and Mackey, 2007) in fisheries, including some small-scale fisheries (Doherty et al., 2014; Mangel et al., 2010; Ortiz et al., 2016). However, use of on-board observers to quantify fishing activities can

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Fig. 1. The camera system developed by Shellcatch Inc. used in our study to monitor catch includes (i) a camera and GPS logger, (ii) a battery pack, (iii) a solar panel to charge the battery, and (iv) a metal frame to mount the camera to the boat. The position where the camera was installed depended on the vessel's configuration. Attachment locations included (a) guard rail (vessel 2); (b) cabin (vessel 3); (c) mast A-frame (vessel 5).

sometimes yield biased information, resulting from deployment effects (Benoît and Allard, 2009), observer effects (Benoît and Allard, 2009; Faunce and Barbeaux, 2011) and low fleet coverage (McCluskey and Lewison, 2008). Monitoring small-scale fisheries through observers poses a major challenge due to the large number of vessels, limited number of trained personnel, low enforcement and vigilance, and difficult working conditions, given the small size of vessels (Salas et al., 2007).

Some vessel monitoring system (VMS) technologies have been developed as an alternative or to supplement on-board observers. VMS is most commonly associated with Geographical Positioning Systems (GPS), but also incorporates other monitoring technologies. VMS is capable of providing data at high spatial and temporal resolution and has been installed in numerous fisheries (Campbell et al., 2014; Gerritsen and Lordan, 2010; Jennings and Lee, 2012; Witt and Godley, 2007), although to date, VMS has been mostly deployed in industrial fisheries, where it is sometimes mandatory (Bertrand et al., 2008). Several aspects of fishing activities can be monitored using VMS, including vessel position, operational characteristics, engine operation, and soak time (Kindt-Larsen et al., 2011; Lee et al., 2010; Vermard et al., 2010). Simple VMS technologies, such as GPS, have been deployed in some small-scale fisheries to monitor their activities (Metcalfe et al., 2016), whilst also providing some direct benefits to the fishermen such as improved navigation (Wildlife Conservation Society Bangladesh, 2016).

One increasingly popular VMS is the use of Remote Electronic Monitoring (REM) cameras, and represents one of the many applications of cameras in marine environmental research (Bicknell et al., 2016). Studies have been carried out to measure the effectiveness of REM systems at monitoring industrial fishing activities, including target catch (Ames et al., 2007; Hold et al., 2015; Kindt-Larsen et al., 2011; Stanley et al., 2009), bycatch (Kindt-Larsen et al., 2012; Pasco et al.,

2009) and the use of bycatch mitigation technologies (Ames et al., 2005). The potential benefits of REM systems to small-scale fisheries research, surveillance and enforcement is high, as it could help improve the understanding of these large, vastly understudied fleets by supplementing or reducing the need for extensive and costly on-board observer programmes.

Within small-scale fisheries, gillnets represent one of the main capture methods for elasmobranchs (Alfaro-Shigueto et al., 2010; Cartamil et al., 2011; Smith et al., 2009). In Peru, it is estimated that approx. 100,000 km of gillnets are set each year by the small-scale fishing fleet (Alfaro-Shigueto et al., 2010), and studies have shown it to have high interaction rates with sea turtles, marine mammals and seabirds (Alfaro-Shigueto et al., 2011; Mangel et al., 2010; Ortiz et al., 2016). Monitoring this large small-scale fishing fleet, with approx. 3000 vessels is a major challenge (Alfaro-Shigueto et al., 2010), and any means of enhancing our ability to understand this small-scale fishery would greatly improve conservation efforts. Our study aimed to assess the ability of REM systems to detect and quantify target and incidental catch in Peru's small-scale elasmobranch gillnet fishery and assess the advantages and disadvantages of using REM technology compared with on-board observers.

2. Methods

2.1. The fishery

Our study monitored 30 fishing trips across 5 vessels from the small-scale fishing ports of San José and Bayóvar in northern Peru from December 2015 to September 2016. Small-scale fishery vessels are defined by Peruvian fishery regulations as having a maximum length of 15 m, a maximum storage capacity of 32.6 m^3, and relying predominantly on manual labour for all fishing activities (Ley General de Pesca, 2001). The vessels used in our study had a mean length of 10.8 m (0.8 m SD; Range 10–12 m; Supplementary Table 1). Our study fishery uses monofilament and multifilament gillnets that are set in the late afternoon by the fishing vessels, and left to soak near the surface or seafloor for approx. 14 h, before being retrieved early the following morning. The nets stay fixed to the vessel drifting throughout the set and are typically 1.5 to 3 km long with a stretched mesh size of 8 to 15 cm. The fishery catches multiple species but primarily targets shark and ray species. The fishery also incidentally captures sea turtles (Alfaro-Shigueto et al., 2011), cetaceans (Mangel et al., 2010), pinnipeds (Alfaro-Shigueto et al., 2010), and seabirds (Awkerman et al., 2006). All fishing vessels and crews were voluntary participants in the study.

2.2. Camera system

The camera system used to monitor the catches on board vessels was developed by Shellcatch Inc. (http://www.shellcatch.com), and comprised a camera and GPS logger, connected to a portable power pack charged by a solar panel (Fig. 1). The camera lens was equivalent to a 35 mm full-frame SLR lens, with a fixed focal length of 3.60 ± 0.01 mm and focal ratio (F-stop) of 2.9. The camera's field of view was set to 53.5 ± 0.1° by 41.4 ± 0.1° and the sensor resolution was set to 2592 by 1944 pixels. The camera was programmed by Shelllcatch Inc. to take photos continuously at 40 s intervals to balance data collection with data management, despite the possibility of missing discarded catch within this interval. The images were recorded to a built-in hard drive and were subsequently downloaded to a computer using cloud data storage software developed by Shellcatch Inc. The entire system was enclosed in a waterproof housing and was installed on each fishing vessel using a metal mount (Fig. 1).

The camera systems were deployed on five fishing vessels. They were mounted in a location to provide maximal coverage of the vessel where catch is processed and to maintain exposure to the sun to charge the battery through the solar panel. The exact location of the camera was decided after consultation with the fishermen, to prevent the camera hindering normal fishing practices, and to ensure some privacy was provided to the fishermen outside of fishing activities. The installation process was also dependent on the exact configuration of each fishing vessel as the fleet is composed of a range of different vessel types, some containing cabins of varying height. The fishermen were asked to undertake normal fishing practices and not to alter their behaviour in the presence of the camera.

2.3. On-board observer data collection

On four of the five fishing vessels, trained on-board observers were additionally present (Supplementary Table 1). Observers recorded the number of individuals captured for all elasmobranch and bycatch species. Identification guides were provided to the observers to aid species identification. Observers also recorded the total length for a subset of the sharks captured (following Romero et al., 2015) and the disc width for a subset of the rays captured (following Ebert and Mostarda, 2016). Catch was recorded using common names, so it was not always possible to distinguish between closely related species that share a common name. Consequently, all target catch analysis was done at the genus level. Participating fishermen were consulted to verify that all common names correctly matched our interpretation.

2.4. Photo analysis

Photos were analysed using GoPro Studio version 2.5.9. This software was used to convert the photos into a time lapse video at 10 frames per second with high image quality (Supplementary Video 1). An analyst subsequently reviewed the videos using QuickTime Player version 10.4. Each haul was analysed frame by frame and each captured animal was recorded. The analyst identified the catch to genus and consulted an expert for assistance when identification was uncertain. Identification was aided by identification guides for each taxon. For a sample of sets ($n = 139$) we recorded the amount of time necessary to complete the photo analysis. The mean time per set was 26.5 ± 11 min (mean ± SD; range 8.3–46.3; n = 139).

2.5. Statistical analysis

2.5.1. Target catch

The on-board observer reports were compared to the photo analyst's observations. The number of individuals of each genus was compared for each haul and the difference between the two methods was calculated. For each fishing vessel, the mean and standard deviation of the number of individuals captured per set was calculated from the observers' reports and the photo analysis. Ratios were calculated by dividing catch quantity from observer reports by catch quantity identified by the photo analyst. As net length could not be estimated from the photos and varied between sets, it was not possible to use the catch per unit effort (CPUE) metric, so catch per set was used in this study. Catch genera were identified by either the observer, the camera or both in each set. A percentage occurrence was calculated for each outcome to determine the ability of the camera to detect each genera.

The mean and standard deviation of the discrepancy between the two methods was also calculated for sets when either the observer or the photo analyst reported catch for each genus. All instances when there was a difference in number of animals landed of the same genus between the observer report and the photo analyst's observations were investigated. After subsequent review of the time lapse video, the likely causes of the discrepancy were identified and attributed to six different categories: camera failure, camera obstruction, insufficient field of view (identified by catch being piled on the edge of the camera's field of view), insufficient light levels, image resolution, or clear deficiencies in the observer reports.

To understand which parameters affect the performance of the cameras, generalised linear mixed effects models (GLMM) with a negative binomial error structure and log link function were undertaken ($n = 362$ species capture events) using package lme4 in R statistical software, version 3.2.3 (Bates et al., 2015; R Core Team, 2014). A negative binomial error distribution was used as our dependent variable (quantity detected by the camera) involved counts with a variance greater than the mean. Sets where no catch was detected by the observers and the camera for each genus were removed, as they were not appropriate for investigations into the factors affecting camera performance, especially when considering the sheer number of zeros (1859 of 2028 possible captures) – most hauls capture only a few genera. Initial models included fixed effect (quantity from observer reports, mean species size and taxon (i.e. shark or ray) and random effect (haul) parameters. Vessel was not included as a random effect as all variation between vessels was accounted for through the inclusion of haul as a random effect. Catch quantity from observer reports was included as a quadratic term to test if the camera performed more effectively with different catch magnitudes. Different genera were divided into three size categories based on the mean total length (sharks) or disc width (rays) for each genus calculated from the size measurements the observers recorded. Genera with a mean length or width ≤ 100 cm were classified into size class A, > 100 cm and ≤ 150 cm as class B, and > 150 cm as class C. Models of all possible combinations of fixed effects were tested using the dredge function in the R package MuMIn (Bartoń, 2017), after the global model was standardised using the standardize function in the arm package (Gelman and Su, 2016). The minimal adequate model was selected based on the lowest Akaike Information Criterion corrected for small sample size (AICc) value (Sakamoto et al., 1986). Initial model selection included the quadratic term for quantity from observer reports in the minimal adequate model, but after model inspection, a quadratic function was not appropriate due to a high heteroscadiscity of model residuals. Instead, a stepwise regression model was undertaken, with an appropriate split point for our dataset identified using the segmented function in the R package segmented (Muggeo, 2003). GLMMs were subsequently undertaken using the same procedure as described above, but with observer quantity included as a linear term, for both small catches (observer quantity ≤ 20; $n = 296$) and large catches (observer quantity > 20; $n = 66$). For larger catches, a Poisson error distribution with square-root link function fitted our data more efficiently, so was used as the model error family. Following this stepwise regression approach, one anomalous point (camera = 179, observer = 1200) was shown to be highly influential on our models, so the stepwise regression procedure was repeated without this extreme value, identifying a new split point for our data. GLMMs were again used to model both small catches (observer quantity ≤ 15; $n = 279$) and large catches (observer quantity > 15; $n = 82$).

2.5.2. Bycatch

A comparison was also made between the observer reports and the photo analyst's observations for bycatch. The detection rate of bycatch when recorded by either the observer or the photo analyst was compared for the two methods. A mean and standard deviation for the detection rates for each vessel was subsequently taken to measure the ability of detecting bycatch using cameras. Due to the low-resolution specifications of the camera, the photo analyst was not always able to identify the bycatch to species level, so all analyses were based on higher taxonomic groupings (cetaceans, pinnipeds, leatherback turtles *Dermochelys coriacea*, hard-shell sea turtles, seabirds). Attempts were made by the photo analyst and three experts to identify the hard-shell sea turtles to species level and these were compared to the observer reports.

3. Results

3.1. Fishing effort

A total of 228 fishing sets from December 2015 to September 2016 across the five fishing vessels were reviewed by the photo analyst and catch was recorded for each set. 89% of sets took place over the continental shelf within 50 km of the coastline. A total of 169 sets were reviewed during the study period across the four vessels with observers present. Initial studies revealed the position of the camera on vessel 2 was not appropriate as the fishermen piled the nets in front of the camera, preventing the photo analyst from seeing much of the catch. Consequently, the camera position was changed and the 12 sets where the problem occurred were excluded from subsequent analyses. Vessel 1 did not have an observer aboard for the initial 14 sets, so these were also excluded from subsequent analyses.

3.2. Target catch

Twelve genera of elasmobranchs were captured and identified by both the observers and the photo analyst across the four vessels with observers present (Fig. 2). One genus (*Sphyrna*) was captured by all four fishing vessels, seven genera (*Carcharhinus*, *Galeorhinus*, *Mobula*, *Mustelus*, *Myliobatis*, *Notorhynchus*, *Squatina*) were captured by three fishing vessels, one genus (*Alopias*) was captured by two fishing vessels and three genera (*Prionace*, *Pteroplatytrygon*, *Triakis*) were captured by only one vessel. For six genera (*Carcharhinus*, *Notorhynchus*, *Mustelus*, *Myliobatis*, *Sphyrna*, *Squatina*), the mean catch recorded by the observers was higher than that identified by the photo analyst (ratios ranging from 0.52 to 1.00). In contrast, the mean catch recorded by the observers was lower than that identified by the photo analyst for five genera (*Alopias*, *Galeorhinus*, *Mobula*, *Prionace*, *Pteroplatytrygon*; ratios ranging from 1.00 to 2.44). There was no discrepancy between the two methods for *Triakis* (Table 1a).

The ability of the cameras to identify the genera caught in each set was investigated for each vessel. For 9 of 12 genera of target catch, the photo analyst was able to detect its capture for > 90% of instances when reported by the observer. Only 3 genera (*Carcharhinus*, *Pteroplatytrygon*, and *Squatina*) were detected by the photo analyst on ≤ 90% of instances when reported by the observer (85%, 82% and 65% respectively; Table 1b).

The discrepancy between the number of individuals caught for each genus was calculated for all sets when either the observer or photo analyst recorded the genus as captured. All genera of elasmobranchs, except *Mustelus* and *Sphyrna*, had a mean discrepancy of < 5 individuals (Table 1c). There were 226 instances when there was a discrepancy between the observer and the photo analyst's reports. Six main problems were identified as the potential cause of the discrepancies: camera field of view ($n = 134$), camera obstructions ($n = 60$), image resolution ($n = 58$), observer failing to record all catch ($n = 51$), camera failure ($n = 45$), and low light levels ($n = 21$; Fig. 3).

GLMMs were undertaken to understand which factors affected the performance of the cameras ($n = 362$ species capture incidences). The effects of quantity, size and whether the catch was a shark or ray were investigated. The variation between different sets was controlled for by a random effect in our model. Quantity and size were retained in our initial minimal adequate model when quantity was included as a quadratic term (MAM; all other models ΔAICc > 2; see Supplementary Tables 2a & 3a). Taxon was not retained in the MAM.

A stepwise regression model was subsequently undertaken with observer quantity as a linear term, with an appropriate split point estimated at 20.74 (1.39 SE; n = 362). GLMMs were undertaken for both small catches (observer quantity ≤ 20; $n = 296$) and large catches (observer quantity > 20; $n = 66$). Observer quantity and taxon were retained in our MAMs for both small and large catches, but size class was no longer identified to influence camera performance. GLMMs

Fig. 2. The target species of the San José and Bayóvar fishery includes several shark and ray species: (a) thresher sharks (*Alopias* spp.), (b) bronze whalers (*Carcharhinus brachyurus*), (c) school sharks (*Galeorhinus galeus*), (d) broadnose sevengill sharks (*Notorhynchus cepidianus*), (e) Blue sharks (*Prionace glauca*) (f) Pacific angel sharks (*Squatina californica*), (g) hammerhead sharks (*Sphyrna* spp.), (h) smoothhound sharks (*Mustelus* spp.), (i) spotted houndsharks (*Triakis maculata*), (j) eagle rays (*Myliobatis* spp.), (k) pelagic stingrays (*Pteroplatytrygon violacea*) and (l) spinetail devil rays (*Mobula japanica*). Images captured using cameras developed by Shellcatch Inc. installed on the fishing vessels involved in our study.

were re-applied after removal of a highly influential anomaly and a new split point was identified at 15.73 (1.23 SE, $n = 361$). For small catches (observer quantity ≤ 15; $n = 279$), observer quantity and taxon were retained in our MAM (see Supplementary Tables 2b & 3b):

$$Camera_i \sim Negative\ Binomial(\mu_i) \Rightarrow e(Camera_i) \sim \mu_i$$

$$\eta_i = 0.673 + \beta_1 \times Observed + \beta_2 \times Shark.\ Ray + a_i$$

$$\log \mu_i = \eta_i$$

where $\beta1 = 0.160$;

$$\beta_2 = \begin{cases} 0, & Shark.\ Ray = Ray \\ -0.327 & Shark.\ Ray = Shark \end{cases};$$

$$a_i \sim N(0, 0.117).$$

For large catches (observer quantity > 15; $n = 82$) observer quantity and size class were retained in our MAM (see Supplementary Tables 2c & 3c):

$$Camera_i \sim Poisson(\mu_i) \Rightarrow (Camera_i)^2 \sim \mu_i$$

$$\eta_i = 3.216 + \beta_1 \times Observed + \beta_2 \times Size.\ Class + a_i$$

Table 1a
Mean catch of each genus per set identified by the cameras installed on the boats and recorded by the observers in their reports for the four vessels with observers present. Catch was measured in terms of numbers of individuals captured.

Species	Common name	1 (N = 15)		2 (*N* = 9)		4 (*N* = 44)		5 (*N* = 101)		Mean (*N* = 4)	
		Camera	Observer reports	Camera	Observer reports	Camera	Observer reports	Camera	Observer reports	Camera	Observer reports
Sharks											
Alopias spp.	Thresher	1.2	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3
Carcharhinus brachyurus	Bronze whaler	0.0	0.0	1.9	1.9	0.1	0.1	0.7	0.7	0.7	0.7
Galeorhinus galeus	School	0.1	0.0	0.0	0.0	0.3	0.3	0.1	0.4	0.1	0.1
Mustelus spp.	Smoothhound	0.0	0.0	3.7	5.9	43.6	84.6	12.5	0.0	10.9	26.6
Notorhynchus cepidianus	Broadnose sevengill	0.0	0.0	0.1	0.3	0.0	0.0	0.4	15.9	0.1	0.2
Prionace glauca	Blue	0.8	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2
Sphyrna spp.	Hammerhead	15.3	21.1	5.7	9.8	0.1	0.1	0.8	0.9	5.5	8.0
Squatina californica	Angel	0.0	0.0	0.0	0.2	0.6	0.7	1.7	1.6	0.6	0.6
Triakis maculata	Spotted houndshark	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
Rays											
Mobula spp.	Devil	0.4	0.0	7.7	4.3	0.0	0.0	0.1	0.1	2.1	1.1
Myliobatis spp.	Eagle	0.0	0.0	2.0	2.7	1.7	1.8	5.4	6.9	2.3	2.8
Pteroplatytrygon violacea	Pelagic stingray	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.1	0.1

$$\sqrt{\mu_i} = \eta_i$$

where $\beta_1 = 0.041$;

$$\beta_2 = \begin{cases} 0, & Size.\ Class = A \\ 1.782 & Size.\ Class = B \end{cases};$$

$a_i \sim N(0, 3.470)$.

This suggests that quantity and taxon influence camera performance for small catches ($x \leq 15$) and that quantity and size category influence camera performance for large catches ($x > 15$). The cameras were more accurate at quantifying catch when catch quantity was low (GLMM, $Z = -12.197$, $p < 0.001$; Supplementary Fig. 1a). For small catches, the camera performed better for rays than sharks (GLMM, $Z = -3.479$, $p < 0.001$). For large catches, the camera performed more accurately for species of medium size (category) than for small species (category A; GLMM, $Z = 3.740$, $p < 0.001$; Supplementary Fig. 1b). It was not possible to measure camera performance for large species (category C) for large catches as no catches for this size class exceeded 15 individuals.

3.3. Bycatch

From 172 sets, observers recorded a total of 33 hard shell sea turtles (19 green *Chelonia mydas*, 9 olive ridley *Lepidochelys olivacea*, 5 unidentified) in 20 sets; 7 dolphins (3 common *Delphinus* spp., 2 dusky *Lagenorhynchus obscurus*, 2 Burmeister's porpoise *Phocoena spinipinnis*) in 7 sets; and 5 South American sea lions *Otaria flavescens* in 2 sets as incidental capture (Fig. 4). The photo analyst recorded a total of 12 turtles, 4 dolphins and 5 seals captured from reviewing the same trips. The photo analyst recorded 3 dolphins in 3 sets and 5 sea lions in 5 sets that were not reported by the observers. No leatherback turtles or seabirds were captured during trips with observers present, but were detected by the cameras on vessels lacking observers (1 leatherback turtle, 1 Humboldt penguin *Spheniscus humboldti*). 48 hard shell sea turtles in 21 sets, 10 dolphins in 7 sets and 6 South American sea lions in 5 sets were also detected by the cameras from 47 sets (9 trips) without an observer present.

The ability of the camera to detect the presence of bycatch was determined for each vessel. Dividing sets of photo analyst detected bycatch by analyst and/or observer detected bycatch determined the camera detection percentage. Sea turtle bycatch had a mean detection of 50% (26% SD; $n = 3$ vessels), whilst the mean detection rate of pinniped bycatch was 100% (0% SD; $n = 2$ vessels) and cetacean bycatch was 80% (36% SD; n = 3 vessels; Table 1b).

Attempts were made by the photo analyst and three experts to identify the 12 hard shell sea turtles detected by the photo analyst for vessels with on-board observers present. On-board observers were assumed to have correctly identified all individuals to species level as they were able to manipulate the animal to facilitate identification. After comparing identifications with those from on-board observers, it was possible to correctly identify the turtles to species level with a mean accuracy of 83% (15% SD). It was not always possible to identify the animal to species level due to limitations in the camera's image resolution.

4. Discussion

Monitoring catch in small-scale fisheries is vital to understanding their impact on aquatic ecosystems. In this study, we present a quantitative assessment of electronic monitoring using cameras in a small-scale fishery setting. Our study showed remote electronic monitoring (REM) to be effective in detecting and quantifying elasmobranch target catch and pinniped bycatch in Peru's small-scale fishery, but not in detecting and quantifying sea turtle and cetacean bycatch. When compared to previous studies looking at similar REM systems in industrial fisheries, REM performed at similar accuracies in our study for both target and incidental catch (Ames et al., 2005; Kindt-Larsen et al., 2011; Pasco et al., 2009; Stanley et al., 2009).

The cameras installed on the fishing vessels were shown to be highly effective at identifying the genera of target catch. In fact, our study showed observers were more likely to fail to report genera captured than the camera failing to detect them. In many of the instances, the photo analyst noted that much of the unreported catch was consumed on-board by the fishermen or was of low economic value, e.g. non-commercial crabs, catfish, rays and small invertebrates. Thus, our study and wider-scale use of REM, could help improve understanding of the population-level impacts on species of low economic value that are consumed by fishermen or discarded, which often remain unreported in small-scale fisheries (Salas et al., 2007).

From our analysis, three features of the catch composition were shown to affect the camera performance at quantifying catch: catch quantity, taxonomic group and mean body size. Firstly, our results show

Table 1b
Probability of detection of each genus of target catch and taxon of bycatch by the cameras and observers for the four vessels with observers present. It should be noted that there may also be instances when both the camera and observers fail to detect catch, but this cannot be directly measured in our study.

Species	Common name	1				2				4				5				Mean (SD)			
		p_B[a]	p_C[b]	p_O[c]	N	p_B[a]	p_C[b]	p_O[c]	N	p_B	p_C	p_O	N	p_B	p_C	p_O	N	p_B	p_C	p_O	N
Target catch																					
Sharks																					
Alopias spp.	Thresher	63%	25%	13%	8	–	–	–	0	–	–	–	0	100%	0%	0%	2	81% (27)	13% (18)	6% (9)	2
Carcharhinus brachyurus	Bronze whaler	–	–	–	0	83%	17%	0%	6	67%	0%	33%	3	67%	22%	11%	9	72% (10)	13% (12)	15% (17)	3
Galeorhinus galeus	School	0%	100%	0%	1	–	–	–	0	86%	0%	14%	7	100%	0%	0%	5	62% (54)	33% (58)	5% (8)	3
Mustelus spp.	Smoothhound	–	–	–	0	100%	0%	0%	3	100%	0%	0%	12	86%	5%	9%	65	94% (7)	2% (3)	5% (5)	3
Notorhynchus cepidianus	Broadnose sevengill	–	–	–	0	100%	0%	0%	1	100%	0%	0%	1	60%	24%	16%	25	87% (23)	8% (14)	5% (9)	3
Prionace glauca	Blue	100%	0%	0%	4	–	–	–	0	–	–	–	0	–	–	–	0	100% (0)	0% (0)	0% (0)	1
Sphyrna spp.	Hammerhead	83%	0%	17%	6	100%	0%	0%	4	100%	0%	0%	3	79%	14%	7%	14	90% (11)	4% (7)	6% (8)	4
Squatina californica	Angel	–	–	–	0	0%	0%	100%	1	88%	13%	0%	8	85%	12%	3%	33	57% (50)	8% (7)	34% (57)	3
Triakis maculata	Spotted houndshark	–	–	–	0	–	–	–	0	–	–	–	0	100%	0%	0%	4	100% (0)	0% (0)	0% (0)	1
Rays																					
Mobula spp.	Devil	0%	100%	0%	4	75%	25%	0%	4	–	–	–	0	80%	20%	0%	5	52% (45)	48% (44)	0% (0)	3
Myliobatis spp.	Eagle	–	–	–	0	100%	0%	0%	2	83%	17%	0%	12	78%	15%	7%	67	87% (12)	11% (9)	2% (4)	3
Pteroplatytrygon violacea	Pelagic stingray	–	–	–	0	–	–	–	0	–	–	–	0	59%	24%	18%	17	59% (0)	24% (0)	18% (0)	1
Bycatch																					
Cetacean		50%	50%	0%	4	–	–	–	0	100%	0%	0%	1	20%	20%	60%	5	57% (40)	23% (25)	20% (35)	3
Pinniped		–	–	–	0	–	–	–	0	0%	100%	0%	2	40%	60%	0%	5	20% (28)	80% (28)	0% (0)	2
Sea Turtle		20%	0%	80%	5	60%	0%	40%	5	–	–	–	0	70%	0%	30%	10	50% (26)	0% (0)	50% (26)	3

[a] *p_B = probability of detection by both the camera and observers.*
[b] *p_C = probability of detection by cameras but not observers.*
[c] *p_O = probability of detection by observers but not cameras.*

Table 1c
Mean discrepancy between catch identified by the cameras and observer reports for each genus for the four vessels with observers present. Catch was measured in terms of numbers of individuals captured.

Genus	Common name	Discrepancy									
		1	N	2	N	4	N	5	N	Mean	N
Sharks											
Alopias spp.	Thresher	0.6	8	–	0	–	0	0.0	2	0.3	2
Carcharhinus brachyurus	Bronze whaler	–	0	0.7	6	0.3	3	0.6	9	0.5	3
Galeorhinus galeus	School	1	1	–	0	0.3	7	0.2	5	0.5	3
Mustelus spp.	Smoothhound	–	0	6.7	3	54.3	37	7.2	66	22.7	3
Notorhynchus cepedianus	Broadnose sevengill	–	0	2.0	1	0.0	1	0.8	25	0.9	3
Prionace glauca	Blue	0.5	4	–	0	–	0	–	0	0.5	1
Sphyrna spp.	Hammerhead	14.3	6	9.3	4	0.0	3	1.6	14	6.3	4
Squatina californica	Angel	–	0	0.0	1	1.4	8	0.8	28	0.7	3
Triakis maculata	Spotted houndshark	–	0	–	0	–	0	0.0	4	0.0	1
Rays											
Mobula spp.	Devil	1.5	4	9.0	4	–	0	0.4	5	3.6	3
Myliobatis spp.	Eagle	–	0	3.0	2	1.3	12	4.9	67	3.1	3
Pteroplatytrygon violacea	Pelagic stingray	–	0	–	0	–	0	0.9	17	0.9	1

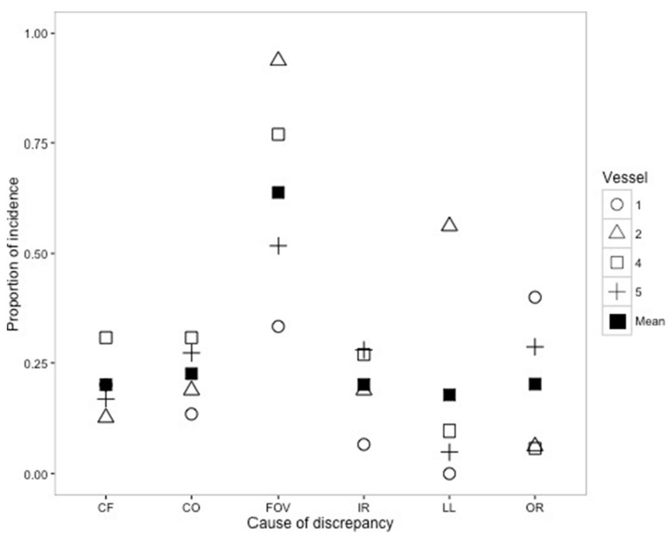

Fig. 3. The proportion of incidence of different factors causing discrepancies in the number of individuals per genus between the observer reports and that identified by the photo analyst for each vessel (1: n = 15; 2: n = 16; 4: n = 52; 5: n = 143). The mean proportion of incidence for the 4 vessels was calculated. The causes of the discrepancies were divided into six different categories: CF – camera failure, CO – camera obstructed by objects or fishermen, FOV – insufficient field of view, IR – insufficient image resolution, LL –low light preventing a clear photo, OR – deficiencies in the observer reports. The camera's field of view was identified as the main factor causing discrepancies between the photo analyst's and observer reports.

that the camera's performance was lower when catch quantity exceeded 15 individuals. With high quantities of catch, the photo analyst was unable to distinguish between individuals as they became piled up, reducing the accuracy of catch estimates. Other studies have also previously found electronic monitoring performance to decline as the catch magnitude increases in mixed-species net fisheries (Lara-Lopez et al., 2012; van Helmond et al., 2015). This finding contrasts to longline fisheries, where several studies showed quantity did not affect catch estimates generated from electronic monitoring (Ames et al., 2005, 2007; Stanley et al., 2009). Our study further emphasises the difficulty of quantifying catch in net fisheries where many individuals are hauled together, unlike longline fisheries where individuals are hauled one by one and can be counted more easily.

Secondly, our study suggests REM is more effective at detecting and quantifying ray species than sharks when catch quantity is below 15 individuals, but not for larger catches. This may be a consequence of the greater surface area of rays compared to sharks, increasing the likelihood of each individual being detected on camera. However, this result might simply be a consequence of the positioning of the cameras on the fishing vessels, with rays more likely to be placed within the camera's field of view than sharks.

Finally, our study has shown that REM performs differentially for different sized target catch genera when catches exceed 15 individuals, with a lower proportion of small-sized animals (size class A: length/width ≤ 100 cm) detected. Few studies have investigated the effect of size on electronic monitoring performance in fisheries (Pasco et al., 2009; van Helmond et al., 2015). Pasco et al. (2009) studied the effect of size on cod bycatch recognition in the Northern Irish *Nephrops* fishery, whilst van Helmond et al. (2015) investigated the effects of mesh size, and coincidentally the size of individuals captured, in the Dutch bottom-trawl fishery on electronic monitoring performance. In both studies, it was shown that quantifying catch was easier for larger individuals, corresponding with our findings.

Our cameras performed less well at detecting and quantifying incidentally caught large vertebrate species, corresponding with the results of previous studies (Ames, 2005; Ames et al., 2007; Pasco et al., 2009). Our study does, however, contrast with the findings of a previous study (Lara-Lopez et al., 2012) who found electronic monitoring to be more effective at quantifying bycatch than target catch in the southern Australian shark gillnet fishery. However, in previous studies the cameras were configured to prioritise monitoring of bycatch (Lara-Lopez et al., 2012), whereas our current study prioritised the location of target catch processing. The difference in priority could explain the contrasting outcomes.

Lower rates of detection for bycatch could also be explained by the length of time catch spends on deck, with unwanted catch released or discarded relatively quickly after it is hauled. Consequently, bycatch may not pass into the camera's field of view during this period. Frame rates have been identified as an issue limiting the effectiveness of electronic monitoring in other studies (Denit et al., 2016; Needle et al., 2014), and the 40 s interval between photos could be a cause of lower performance in our study. Moreover, sea turtles and cetaceans can damage nets and pose a major challenge to haul aboard for fishermen, especially those that rely predominantly on manual labour, meaning much bycatch is not brought on deck. Many incidentally caught individuals will also drop out of the net before reaching the deck (Bravington and Bisack, 1996; Kindt-Larsen et al., 2012). Consequently, these animals that fail to reach the deck will never enter the camera's field of view, but may still be detected by observers. Following investigations into the cause of discrepancies between observer and photo analyst reports, the majority were attributed to aspects of the camera's specification that were kept low to aid data storage and management. It

Fig. 4. Several species are also caught incidentally in the fishery: (a) common dolphins (*Delphinus* spp.), (b) dusky dolphin (*Lagenorhynchus obscurus*), (c) olive ridley turtle (*Lepidochelys olivacea*), (d) leatherback turtle (*Dermochelys coriacea*), (e) South American sea lion (*Otaria flavescens*) and (f) Humboldt penguin (*Spheniscus humboldti*). Images captured using cameras developed by Shellcatch Inc. installed on the fishing vessels involved in our study.

is expected overall performance will improve through modifications to the camera's specifications, as found in previous studies (Ames et al., 2007).

The use of REM could provide a lower cost alternative to the on-board observer programme. Based on estimated costs of our observer programme and electronic monitoring systems, including installation, servicing, data storage and wage costs, REM systems offered savings of approx. 50% per vessel monitored. Unlike on-board observers who have to be at sea for the duration of the fishing trip, photo analysts can review a day's fishing in under 30 min. Electronic monitoring also overcomes other challenges of monitoring small-scale fisheries, such as space limitation for observers, security at sea in small vessels and large fleet sizes. Kindt-Larsen et al. (2012) showed electronic monitoring could provide > 50% savings over observer programmes, although this is likely attributed to higher wages in the study country. Financial savings from electronic monitoring could allow for a substantial increase in fleet coverage compared to on-board observers. Advancements in technology and decreasing costs of data storage mean electronic monitoring is likely to become an even cheaper alternative, whilst providing more accurate data.

Our study has revealed many advantages and disadvantages of using REM and on-board observers to monitor the catch of small-scale fisheries (Table 2). REM has the potential to replace or supplement on-board observers to monitor small-scale fisheries, which remain widely unmonitored and unstudied globally (Berkes et al., 2001; Lewison et al., 2004; Mohammed, 2003; Pauly, 2006). The potential applications of electronic monitoring in small-scale fisheries are numerous. When combined with GPS data it can provide a powerful tool to identify fishing grounds, areas of high bycatch risk and other important data for fishery management and conservation (Gerritsen and Lordan, 2010; Jennings and Lee, 2012; Witt and Godley, 2007). Moreover, recent studies have identified effective bycatch mitigation technologies for small-scale fisheries (Mangel et al., 2013; Ortiz et al., 2016; Peckham et al., 2016) and REM could supplement observer data to improve accuracy, monitor their effectiveness and enforce their use. With an appropriate regulatory or enforcement structure, REM could also be used to monitor illegal fishing practices, such as the shark finning trade (Worm et al., 2013).

Despite its potential to improve fisheries' monitoring, concerns regarding the effectiveness of electronic monitoring systems remain (Association for Professional Observers, 2016). Some of these could more easily be overcome, such as through modifications to the camera specifications (e.g. frame rate), but others relate to the inherent nature of these systems. Camera systems can be manipulated, may be poorly maintained and are vulnerable to hidden activity outside their field of view. Consequently, in some cases, actions may be required to overcome these limitations, such as installation of multiple cameras or penalties for violations.

Although the use of REM could help increase the coverage of small-scale fisheries, the vast nature of these fishing fleets remains a great challenge. Peru's small-scale fisheries alone are composed of nearly 10,000 vessels (Alfaro-Shigueto et al., 2010), meaning full coverage remains unlikely. Nevertheless, REM has the potential to dramatically advance our understanding of small-scale fishery interactions with elasmobranchs and other threatened taxa (a key research priority e.g. Rees et al., 2016). Any method that increases the quality and quantity of data can ultimately only help inform and improve conservation actions.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2018.01.003.

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Table 2
The advantages and disadvantages to using cameras and on-board observers to monitor catch and bycatch in small-scale fisheries as highlighted by our study.

Factor	Cameras	On-board observers
Boat coverage	Dependent on field of view and positioning of the camera	Whole vessel coverage
Fleet coverage	Potentially high	Difficult to implement on a large spatial and temporal scale
Bias	Independent analyst	Fishermen may not report truthfully or may change activity in the presence of an independent observer
Species identification	Analyst can review multiple times and can consult an expert. Dependent on visual cues	Identification once and in real-time, unless pictures taken. Can use multiple cues to identify (visual, smell, touch)
Animal manipulation	Angle and visual cues dependent on camera	Observer can alter position to aid identification
Biological sampling	Not possible	Possible
Re-analysis	Possible	Not possible, unless pictures taken
Image quality	Camera resolution	Human eye
Data intensity	Data intensive	Data non-intensive
Data processing	Same time as analysis	Subsequent entry – commonly hand written and then added to electronic database. Use of apps and computer programs on-board the exception
Automation	Potential for artificial intelligence	None
Catch per unit effort (CPUE) calculation	Difficult to estimate net length, but soak time estimate possible	Possible
Human hours	Low– < 30 min to analyse each set	High - Observer required to be onboard for duration of trip
Cost	Medium	High
Vessel accommodation	Little space required	Space to occupy an extra person on-board required

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