Calibration of pelagic stereo-BRUVs and scientific longline surveys for sampling sharks

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Julia Santana-Garcon [a, *], Matias Braccini [b], Tim J. Langlois [a], Stephen J. Newman [b, c], Rory B. McAuley [b] and Euan S. Harvey [c]

[a] The UWA Oceans Institute (M470) and School of Plant Biology, Faculty of Natural and Agricultural Sciences,, The University of Western Australia, Crawley 6009 Western Australia, Australia.

[b] Western Australian Fisheries and Marine Research Laboratories, Department of Fisheries, Government of Western Australia, P.O. Box 20, North Beach 6920, Western Australia, Australia.

[c] Department of Environment and Agriculture, School of Science, Curtin University, Bentley Campus 6485, Western Australia, Australia.

*Corresponding author. Tel.: +61 6488 4733
Email address: j.santanagarcon@grs.uwa.edu.au

Abstract

1. Our understanding of the ecology of sharks and other highly mobile marine species often relies on fishery-dependent data or extractive fishery-independent techniques that can result in catchability and size-selectivity biases. Pelagic Baited Remote Underwater stereo-Video systems (pelagic stereo-BRUVs) provide a standardised, non-destructive and fishery-independent approach to estimate biodiversity measures of fish assemblages in the water column. However, the performance of this novel method has not yet been assessed relative to other standard sampling techniques.

2. We compared the catch composition, relative abundance and length distribution of fish assemblages sampled using pelagic stereo-BRUVs and conventional scientific longline surveys. In particular, we focused on sharks of the family Carcharhinidae (requiem sharks) to assess the sampling effectiveness of this novel technique along a latitudinal gradient off the coast of Western Australia. We calibrated the sampling effort required for each technique to obtain equivalent samples of the target species and discuss the advantages, limitations and potential use of these methods to study highly mobile species.

3. The proportion of sharks sampled by pelagic stereo-BRUVs and scientific longline surveys was comparable across the latitudinal gradient. *Carcharhinus plumbeus* was the most abundant species sampled by both techniques. Longline surveys selected larger individuals of the family Carcharhinidae in comparison to the length distribution data obtained from pelagic stereo-BRUVs. However, the relative abundance estimates (catch per unit of effort) from the pelagic stereo-BRUVs were comparable to those from 5 to 30 longline hooks.

4. Pelagic stereo-BRUVs can be calibrated to standard techniques in order to study the species composition, behaviour, relative abundance and size distribution of highly mobile fish assemblages at broad spatial and temporal scales. This technique offers a non-destructive fishery-independent approach that can be implemented in areas that may be closed to fishing, and is suitable for studies on rare or threatened species.

Keywords: Baited Remote Underwater Video, fishery-independent, method comparison, effort equivalence, gear selectivity, Carcharhinidae, pelagic fish, mid-water, behaviour, marine ecology

Introduction

Emerging technologies are providing new options for cost-effective ecological sampling. These technical advances dramatically increase the opportunities for *in situ* ecological and behavioural research in vast and remote environments such as the open ocean (Murphy & Jenkins 2010). However, in order to understand the potential of novel techniques it is necessary to compare and calibrate them against traditional methods.

Studying the ecology and assessing the status of sharks is challenging due to their generally high mobility, ontogenetic shifts in habitat preference and broad geographic range (Dulvy *et al.* 2008). Our understanding on the biology and ecology of sharks and other highly mobile marine species largely relies on fishery-dependent data from commercial and recreational fisheries (Myers & Worm 2003). The use of fishery-dependent data alone can lead to sampling biases due to gear selectivity and heterogeneous fishing effort that discriminate among species and habitats (Simpfendorfer *et al.* 2002; Murphy & Jenkins 2010). Alternatively, fishery-independent surveys use more robust sampling designs, but often employ the same commercial fishing gear (e.g. longlines, gillnets, trawls) and as such, catchability and size-selectivity biases remain (McAuley, Simpfendorfer & Wright 2007).

Scientific longline surveys are among the most commonly used fishery-independent methods for studying the demography and ecology of shark populations (Simpfendorfer *et al.* 2002). These surveys provide measures of relative abundance, sex ratio and length distribution of a range of shark species (McAuley *et al.* 2007). Additionally, longlines allow the collection of samples for population biology studies (e.g. genetics, age, growth, reproduction, diet) and the deployment of conventional and electronic tags (Meyer, Papastamatiou & Holland 2010). However, in order to obtain length or biomass data from longline surveys, sharks must be caught, retrieved and handled out of the water. The handling of sharks aboard research vessels aims to maximise survival of individuals, but all captured fish are exposed to varying degrees of physiological stress and physical trauma that can induce pre- or post-release mortality (Skomal 2007). Consequently, these extractive techniques may not be suitable for sampling rare or threatened species, or used in areas that are closed to fishing (Murphy & Jenkins 2010).

Baited Remote Underwater Video systems (BRUVs) provide an alternative standardised, non-extractive and fishery-independent approach that is widely used to estimate biodiversity indices and relative abundance measures of a range of marine species (Cappo *et al.* 2003; Langlois *et al.* 2012b; Santana-Garcon *et al.* 2014), including sharks (Brooks *et al.* 2011; Goetze & Fullwood 2013; White *et al.* 2013). This technique uses bait to attract individuals into the field of view of a camera so that species can be identified and individuals counted (Dorman, Harvey & Newman 2012). When stereo-camera pairs are used, precise length measurements can be made and biomass estimated (Harvey *et al.* 2010). Pelagic stereo-BRUVs are a novel method that sets camera systems at a predetermined depth in the water column as opposed to the commonly used benthic deployment where stereo-BRUVs are set on the seafloor. This deployment design allows pelagic stereo-BRUVs to estimate the composition, relative abundance and length distribution of fish assemblages that inhabit the water column (Heagney *et al.* 2007; Santana-Garcon, Newman & Harvey 2014).

Methodological comparisons assist in validating the utility of innovative sampling methods and to understand the advantages and limitations of different techniques. The use of benthic BRUVs to survey demersal fish assemblages has been compared to scientific fishing surveys including trawl (Cappo, Speare & De'ath 2004), trap (Harvey *et al.* 2012b), hook and line (Langlois *et al.* 2012a), and longline (Ellis & Demartini 1995). Additionally, benthic BRUVs and scientific longline surveys were compared to estimate the diversity and relative abundance of sharks in the Bahamas (Brooks *et al.* 2011). These studies found that the species composition determined with baited video techniques differed to the catch of trawls (Cappo, Speare & De'ath 2004) but it was comparable to some extent to the catch of traps and longlines (Brooks *et al.* 2011; Harvey *et al.* 2012b). Estimates of relative abundance differed among techniques, especially for rare species (Brooks *et al.* 2011; Harvey *et al.* 2012b). However, differences in length distribution of species taken in traps and hooks or recorded on stereo-BRUVs were not biologically significant (Langlois *et al.* 2012a). Pelagic stereo-BRUVs have been used to assess pelagic fish assemblages (Santana-Garcon, Newman & Harvey 2014) but their performance has not been assessed relative to other sampling techniques.

The present study aims to compare the catch composition, relative abundance and length distribution of fish sampled by pelagic stereo-BRUVs and conventional scientific longlines. The sampling effort required for each technique to obtain equivalent relative abundance samples is determined for each of the target species. In particular, surveys were conducted along a latitudinal gradient off the coast of Western Australia to target sharks of the family Carcharhinidae, commonly known as requiem sharks. Given that longlines used large hooks to target sharks, we hypothesised that the methods would differ in total catch composition with pelagic stereo-BRUVs providing data on a broader range of species. However, we expect that both methods would generate comparable estimates of relative abundance and length distribution for the targeted shark species. Finally, the advantages and limitations of pelagic stereo-BRUVs and scientific longline surveys to study highly mobile species are discussed.

Methods

SAMPLING TECHNIQUE

We conducted a longline and pelagic stereo-BRUVs survey in August 2012 at 10 sites over 950 km along the coastline of Western Australia (Fig. 1). Sites were 15 to 80 km offshore at depths ranging between 35 and 106 metres, although most sites were 40 to 60 metres deep. Data were recorded from 31 pelagic stereo-BRUVs and 31 scientific longline deployments targeting requiem sharks. Three replicate deployments of each method were conducted simultaneously at each site, with the exception of one site in the Houtman Abrolhos Islands where four replicates of each technique were undertaken. The number of replicates for each method was limited by logistical constraints of this research expedition. During deployment, both methods were interspersed following a straight line with a separation of at least one kilometre between deployments of either method to avoid or minimize potential overlap of bait plumes and, to reduce the likelihood of fish moving between replicates.

Scientific longline surveys

Scientific longline surveys were conducted as part of the annual shark monitoring and tagging program of the Department of Fisheries (Western Australia). Surveys were designed to target requiem sharks. The longlines were 500 m in length and comprised ~50 J-shaped hooks of size 12/0 baited with Sea Mullet (*Mugil cephalus*; half a fish per hook) and attached to the main line via 2 m metal snoods (Fig. 2a). Lines were designed to hold hooks approximately 8 metres above the seafloor. However, hooks near the ballast remained closer to the bottom; this was confirmed during retrieval as fragments of benthos such as sponges were occasionally caught (Santana-Garcon *pers. obs.*). Longlines were set before dawn at ~5 am and soak time ranged between 2.5 and 6 hours, depending on the time required for retrieval and processing of the catch. Upon retrieval, all individuals caught were identified to the species level and their fork length (FL) was measured. Catch per unit of effort (CPUE), a measure of abundance where catch is standardised across deployments of different sampling effort, was calculated as the catch of each longline divided by the soak time (hours) and the number of hooks used. In the present study, we defined CPUE10 as the catch per hour per 10 hooks as a measure to facilitate comparison between methods (the number of hooks was chosen on the basis of results presented herein).

Pelagic stereo-BRUVs

Pelagic stereo-BRUVs were adapted to match the deployment characteristics of longlines so that both methods sampled at similar depths, for equal periods of time and using the same bait. During the deployment of pelagic stereo-BRUVs, cameras were placed in the mid-water, approximately 8 to 10 metres above the bottom (Fig. 2b). This technique uses ballast and sub-surface floats in order to anchor the systems, enabling control over the deployment depth and reducing movement from surface waves (Santana-Garcon, Newman & Harvey 2014). The camera systems consisted of two Sony CX12 high definition digital cameras mounted 0.7 m apart on a steel frame and converged inwards at 8 degrees to allow the measurement of fish length (Harvey *et al.* 2010). The bait consisted of 1 kg of mullet (*Mugil cephalus*; fish cut in halves) in a wire mesh basket suspended 1.2 m in front of the cameras. As for longlines, camera deployments were set before dawn, at 5 am in the morning, and soak time ranged between 2.5 and 6 hours depending on the time required for longline retrieval.

Videos were analysed for the full length of the deployment. A blue light (wavelength 450-465 nm) was fitted on the frame, between the cameras, in order to illuminate the field of view during the sampling hours before dawn. Blue light wavelength is thought to be below the spectral sensitivity range for many fish species (Von Der Emde, Mogdans & Kapoor 2004), and therefore, it is expected to have minimal impact on fish behaviour (Harvey *et al.* 2012a).

VIDEO ANALYSIS

Stereo-camera pairs were calibrated before and after the field campaign using CAL software (SeaGIS Pty Ltd) following Harvey & Shortis (1998). The video images obtained from pelagic stereo-BRUVs were analysed using the software 'EventMeasure (Stereo)' (SeaGIS Pty Ltd). All fish observed were quantified, identified to the lowest taxonomic level possible and measured. However, for this study, small pelagic fish species in the family Clupeidae and small carangids from the genus *Decapterus*, *Selar* and *Selaroides* among others were excluded from the analysis. A conservative measure of relative abundance, MaxN, was recorded as the maximum number of individuals of the same species appearing in a frame at the same time. MaxN avoids repeat counts of individual fish re-entering the field of view (Priede *et al.* 1994; Cappo *et al.* 2003). MaxN per hour was used in order to standardise sampling effort across all deployments due to variable soak times. Length measurements (FL) were made from the stereo-video imagery for each individual within 7 metres of the camera system recorded at the time of MaxN. Individuals must be measured when their body is straight which can be difficult for sharks given their swimming behaviour, as such, in order to improve the accuracy of shark measurements, the length of each individual was determined from an average of five measurements obtained in different video frames (Harvey, Fletcher & Shortis 2001).

STATISTICAL ANALYSIS

Comparison of catch composition

Differences in species composition between scientific longlines and pelagic stereo-BRUVs were tested using one-way univariate permutational analysis of variance (PERMANOVA; Anderson, Gorley & Clarke 2008). Proportional data facilitates the comparison of composition patterns sampled by each method as it standardises all samples to the same scale (Jackson 1997). Hence, for each of the five species of requiem sharks recorded, we used proportional data to emphasise the contribution of each species to the total number of individuals caught per deployment and method. Proportional data were calculated from CPUE data across all replicates and were arcsine transformed to normalise possible binomial distributions (Zar 1999). Euclidean distance was used to generate the dissimilarity matrices (Anderson *et al.* 2011), P-values were obtained using permutation tests (9,999 permutations) for each individual term in the model and, Monte Carlo p-values were used to interpret the result when the number of unique permutations was less than 100 (Anderson 2001). Data manipulation and graphs across the study were undertaken using the packages 'reshape2'(Wickham 2007), 'plyr' (Wickham 2011) and 'ggplot2'(Wickham 2009) in R (R Core Team 2013).

Catch comparison along a latitudinal gradient

The ability of the two methods to describe spatial patterns along a latitudinal gradient (32° to 24° S) was compared. For each of the target species, a one-way analysis of covariance (ANCOVA) was conducted with method as a factor and latitude as a covariate. A significant interaction between latitude and method would indicate that the methods were not comparable across the latitudinal range. Analyses were based on Euclidean distance resemblance matrices calculated from arc sine transformed proportional data. Statistical significance was tested using 9,999 permutations of residuals under a reduced model.

Equivalence of sampling effort

For the target species, the equivalent longline and pelagic stereo-BRUVs sampling effort was determined by performing a series of statistical tests on the abundance estimates obtained from BRUVs (MaxN per hour) and from a range of longline effort data sets (1-50 hooks). Random samples of our data were taken with replacement and the differences between methods were tested using univariate PERMANOVAs based on Euclidean distance resemblance matrices of the raw CPUE data, with method as a fixed factor (Anderson *et al.* 2011). P-values were obtained from 9,999 permutations using the 'adonis' function from the 'vegan' package (Oksanen *et al.* 2013) in R. This process was bootstrapped (1000 times) to generate a distribution of p-values across sampling efforts for the target species.

Additionally, we compared the sampling precision of both techniques at the family level and for each target species. The precision of a sampling method refers to the repeatability of its measurements under unchanged conditions, it can be expressed numerically by measures of imprecision like standard deviation, variance and most commonly, as a ratio of the standard error (SE) and the mean (Andrew & Mapstone 1987). Here, we estimated precision (p) as $p = SE / Mean$, where the mean and standard error were obtained from the abundance per deployment for each sampling technique.

Comparison of length distributions

For the target species, length distributions obtained from pelagic stereo-BRUVs and longline surveys were compared using kernel density estimates (KDE). The KDE method is sensitive to differences in both the shape and location of length distributions (Sheather & Jones 1991). KDE analyses were conducted using the R packages 'KernSmooth' (Wand 2013) and 'sm' (Bowman & Azzalini 2013) following the method described by Langlois et al. (2012a). For each species, the statistical analysis between the pairs of length distributions collected by each method was based on the null model of no difference and a resulting permutation test. The statistical test compared the area between the KDEs for each method to that resulting from permutations of the data into random pairs. To construct the test, the geometric mean between the bandwidths for stereo-BRUVs and longline data were calculated (Bowman & Azzalini 1997). If the data from both methods have the same distribution, the KDEs should only differ in minor ways due to within population variance and sampling effects (Langlois *et al.* 2012a). The 'sm.density.compare' function in the 'sm' package was used to plot the length distributions where the resulting grey band shows the null model of no difference between the pair of KDEs.

Results

Comparison of catch composition

Scientific longline surveys used 1,671 baited hooks (125 hours) and caught 236 individuals of 18 different species. Pelagic stereo-BRUVs recorded 123 hours of video in 31 deployments with a total of 124 individuals of 20 species identified. The numerous small pelagic fish (TL < 250 mm) observed in the video were not included in the species count or in the analyses. Teleost species were almost exclusively sampled by pelagic stereo-BRUVs, while the semi-pelagic sharks were sampled by both methods (Fig. 3). Due to the deployment design of longlines, a proportion of the hooks adjacent to the ballast were set close to the bottom and, consequently, benthic sharks were almost exclusively sampled by this method.

The target shark species caught included sandbar *Carcharhinus plumbeus,* tiger *Galeocerdo cuvier,* blacktip *C. limbatus/tilstoni* and milk *Rhizoprionodon acutus* sharks, and *Carcharhinus spp**. The latter combines four requiem species that could not be confidently distinguished across all videos (bronze whaler *C.brachyurus*, dusky *C.obscurus*, spinner *C.brevipinna* and spot-tail *C.sorrah* sharks). The common blacktip *C. limbatus* and the Australian blacktip *C. tilstoni* sharks are also combined here as there are no external morphological features that distinguish these species (Harry *et al.* 2012).

For each of the target species, there was no significant difference in the proportion sampled by either method ($P > 0.05$; Fig. 4). The sandbar shark *C. plumbeus* was the most abundant species for both methods followed by *Carcharhinus spp** (Figs. 3 and 4). Using pelagic stereo-BRUVs, the third and fourth most abundant species were *G. cuvier* and *C. limbatus/tilstoni*, whereas with longlines these species were the fourth and third most abundant respectively. *Rhizoprionodon acutus* was the least abundant and it was rarely recorded by either method.

Catch comparison along a latitudinal gradient

Pelagic stereo-BRUVs and scientific longline surveys showed similar patterns of abundance for all target species along the 950 km latitudinal gradient (Fig. 5). The ANCOVA revealed no significant interaction between method and latitude for any of the target species ($P > 0.05$). The species proportional abundance did not differ significantly between methods whereas latitude had a significant effect on the distribution of *C. plumbeus* with a greater abundance present in the northern sites (Table 1). *Rhizoprionodon acutus* and *C. limbatus/tilstoni* also showed a significant effect of latitude in their distribution as they were only recorded north of Shark Bay, the most northern sampling sites (~24° S). Although strong patterns were apparent for *G. cuvier* and the species complex (*Carcharhinus spp**), there was no significant effect of latitude or method.

Equivalence of sampling effort

PERMANOVA tests on bootstrapped CPUE data and a range of sampling efforts indicated that the relative abundance of requiem sharks obtained from each camera system (MaxN per hour) is statistically comparable ($P > 0.05$) to a sample obtained from 5 to 30 hooks with similarities peaking at 12 hooks (Fig. 6). This range of effort equivalence for requiem sharks is largely driven by *C. plumbeus*, the most abundant species in this study. The range of equivalence varied among species, for *C. plumbeus* effort equivalence ranged between 3 and 30 hooks, with similarities peaking at 10 hooks. *Carcharhinus spp** and *G. cuvier* showed no significant difference between methods when MaxN per hour was compared to the catch of 1 to 50 hooks but similarities peaked at 24 and 21 hooks, respectively. Results for *C. limbatus/tilstoni* and *R. acutus* were inconclusive due to the low abundance recorded with both techniques.

Precision estimates of pelagic stereo-BRUVs and scientific longline surveys were similar for the Carcharhinidae family, *C. plumbeus*, *G. cuvier* and *C. limbatus/tilstoni* (Table 2). For *Carcharhinus spp** and *R. acutus*, estimates obtained from longline surveys were more precise. Note that, as the values of p decrease, the precision of the sampling technique improves. We found that both techniques were considerably less precise at sampling uncommon species compared to the more abundant species. Precision values of 1 indicate that individuals of that species were only recorded in one deployment.

Comparison of length distributions

There were no significant differences in the shape of the length distributions sampled with both methods for the family Carcharhinidae and, at the species level, for *C. plumbeus*, *Carcharhinus spp** and *G. cuvier*. However, there were significant differences in the location (i.e. mean length) of the length distributions for the Carcharhinidae and, at the species level, for *C. plumbeus*. For these taxa, longline surveys were more selective of larger individuals (Table 3, Fig. 7). Standard error bands are wide for those species with small sample sizes; therefore the interpretation of the results should be undertaken with caution.

Discussion

We demonstrated that pelagic stereo-BRUVs provide an alternative non-lethal method of sampling sharks that can be calibrated with standard methods such as scientific longline surveys. The proportion of Carcharhinidae species sampled by pelagic stereo-BRUVs and scientific longline surveys was comparable across the study. Pelagic stereo-BRUVs provided a comparable estimate of Carcharhinidae species that is proportional to longline surveys, whilst also providing abundance information on other teleost species that were not targeted or captured by longlines due to the selectivity of the hooks. Longlines sampled a greater proportion of benthic shark species due to the deployment design that set hooks adjacent to the ballast in close proximity to the benthos.

The species composition of the Carcharhinidae between the two methods was also consistent across a broad latitudinal gradient. These findings support previous studies that define baited video techniques as a suitable, standardised and non-extractive approach to study the distribution of mobile species across broad spatial scales (Langlois *et al.* 2012b; White *et al.* 2013). In the current study, *C. plumbeus* was the most abundant requiem shark species captured by both sampling methods. It was recorded throughout the study area, but in greater numbers at the northern sites. *Galeocerdo cuvier* and the *Carcharhinus spp** complex also occurred throughout the study area, and showed no significant pattern along the latitudinal gradient for either method. *Carcharhinus limbatus/tilstoni* and *R.acutus* were only recorded in the most northern sites.

Each pelagic stereo-BRUV system yielded equivalent relative abundance estimates for requiem sharks to that of 5 to 30 hooks in scientific longlines. Effort equivalence between techniques peaked at 12 hooks for requiem sharks and, at the species level, effort equivalence peaked at 10, 21 and 24 hooks for *C. plumbeus*, *G. cuvier* and *C. spp**, respectively. Due to logistic constraints we could only deploy one camera system for every longline (50 hooks). Although the target species composition and relative abundance derived from these techniques were comparable, in absolute terms longlines caught a greater number of individuals of the target species (159) than those recorded at MaxN on BRUVs (36). In addition, it should be noted that the methods differed in the area covered and in the amount of bait used. Longline shots, with a length of 500 m each and more than 10 times the amount of bait in the water, have a greater ability to attract or encounter fish than a single baited camera system (Brooks *et al.* 2011). Thus, increasing sampling effort of the non-extractive pelagic stereo-BRUVs to approximately one camera deployment for every 10 to 24 hooks is recommended to exert a sampling effort equivalent to the commonly used scientific longline surveys.

Precision estimates for both techniques were similar at family level and for the most abundant target species. Precision is most affected by sampling effort; thus increasing replication would rapidly enhance sampling precision (Andrew and Mapstone, 1987). In this study, the number of deployments of pelagic stereo-BRUVs per site was limited by the complexity of using two methods at once. However, future studies using this technique could deploy more camera systems simultaneously, which would rapidly boost replication without added field-time cost (Santana-Garcon, Newman & Harvey 2014) and, in turn, it would rapidly enhance their sampling precision.

Stereo-BRUVs remove biases due to gear selectivity, such as hook size, that are an undesired by-product of conventional fishing methods (Cappo *et al.* 2003). In the present study, longline surveys were selective towards larger individuals of the family Carcharhinidae in comparison to pelagic stereo-BRUVs. At the species level, size selectivity was only significant for *C. plumbeus*, but KDE tests for other shark species might lack power to detect differences between methods due to the small sample sizes available ($N < 50$) (Bowman & Azzalini 1997). Mean fork length of *C. plumbeus* (1280 mm) and *C. spp** (1627 mm) recorded from longline surveys were larger than those recorded from stereo-BRUVs (1089 and 1534 mm). Conversely, tiger sharks were on average larger on stereo-BRUVs (2028 mm) in comparison to longlines (1823 mm). Previous studies have shown species-specific differences in the length distributions of fish sampled with stereo-BRUVs and line fishing (Langlois *et al.* 2012a), or traps (Harvey *et al.* 2012b) but the differences reported were not biologically significant. In the present study, low replication was a major limitation in the analysis of length distributions; hence, further research is needed to continue exploring the differences between size selectivity of longlines and pelagic stereo-BRUVs.

Video techniques have proven to be non-intrusive, causing no physical trauma or physiological stress to the individuals recorded (Brooks *et al.* 2011). Despite attempts to minimise the impact on sharks caught in longline surveys, mortality does occur and the level of post-release mortality is not known (Skomal 2007). The non-destructive nature of stereo-BRUVs allows for deployment in fragile and protected areas and reduces the negative effects of extractive gears when targeting rare and threatened species (White *et al.* 2013). Additionally, remote video techniques provide a permanent record of species behaviour in their natural environment (Zintzen *et al.* 2011; Santana-Garcon *et al.* 2014). A recurrent behaviour across shark species observed during video analysis was that individuals were first observed far from the camera system but remain in the area patrolling the bait source. They approach the bait in a cautious manner over time. This behaviour suggests that longer soak times facilitate the recognition of individual features including species, sex or external markings. Nonetheless, this territorial behaviour could also prevent other individuals of the same or other species from approaching the cameras, which could affect estimates of species composition and relative abundance (Klages *et al.* 2014).

Many species of the family Carcharhinidae are externally similar and visual identification can be difficult. Identification of individuals to species level from video alone is the main limitation of pelagic stereo-BRUVs to study requiem sharks (Santana-Garcon, Newman & Harvey 2014). Species identification can also be restricted in fishery-dependent methods, species may be misidentified or pooled under general categories (Walker 1998). Identifying features of requiem sharks are often subtle and the most important of these are tooth shape and numbers, position of the dorsal fins, colour, and the presence or absence of an interdorsal ridge. These features can be difficult to assess during the rapid processing of sharks caught on longlines and this is exacerbated when using remote video techniques. Although most species could be distinguished on video when individuals come close to the cameras, identification of some species across all replicate videos may not be possible. Another constraint of video techniques, although not assessed in this study, are limitations to identifying the sex of individuals. Claspers of mature males were often visible, but identification of females and young males with uncalcified claspers was more challenging. The lack of this information could limit the use of video techniques in studies of intra-species demographics (Brooks *et al.* 2011). However, advances in high-definition digital video and automation of the identification of key morphological characteristics could improve the rates of identification of species, sex and even discrimination between individuals (Harvey *et al.* 2010; Shortis *et al.* 2013).

This assessment of the novel pelagic stereo-BRUVs and its comparison to the commonly used scientific longline surveys provides a better understanding of the strengths and limitations of each technique. The two methods produce comparable estimates of relative abundance and species composition for requiem sharks, and the choice of sampling technique in future should depend on the specific aims of the study. Scientific longline surveys continue to be a more appropriate approach for research targeting species that could not be confidently identified on video, or studies on population biology that require finer intra-specific information such as sex ratio or reproduction information, the collection of tissue samples (e.g. genetic and isotopic analyses), or the implantation of conventional or electronic tags (McAuley *et al.* 2007). Stereo-BRUVs, however, provide a suitable sampling method that can be calibrated to standard techniques for studies with broad spatial and temporal scales, directed at questions of species composition, behaviour, relative abundance and size distribution of fish assemblages (Watson & Harvey 2009; Langlois *et al.* 2012b; Santana-Garcon *et al.* 2014), including highly mobile species (Brooks *et al.* 2011; White *et al.* 2013; Santana-Garcon, Newman & Harvey 2014). Furthermore, studies conducted on rare or threatened species, and in areas that are closed to fishing might require a non-intrusive approach like baited video techniques (White *et al.* 2013). Our study demonstrated that pelagic stereo-BRUVs can provide comparable information to longline surveys on the relative abundance and size composition of requiem sharks, and determined the required sampling effort to calibrate both methods.

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TABLES:

Table 1. Summary of ANCOVA tests with method as factor and latitude as covariate. Abundance data was collected with pelagic stereo-BRUVs and scientific longline surveys along an 8-degree latitudinal gradient. P-values in bold are statistically significant.

	Latitude	Method	La x Me
Carcharhinus plumbeus	**<0.001**	0.878	0.108
*Carcharhinus spp**	0.486	0.291	0.571
Galeocerdo cuvier	0.350	0.226	0.208
Carcharhinus limbatus/tilstoni	**0.022**	0.682	0.303
Rhizoprionodon acutus	**0.003**	0.834	0.410

Table 2. Precision estimates for target species sampled using pelagic stereo-BRUVs and scientific longline surveys. Precision (*p*) was estimated as a ratio of the standard error and the mean abundance per deployment. Note that lower values of *p* indicate better precision.

	p BRUVs	*p* Longlines
Family Carcharhinidae	0.236	0.206
Carcharhinus plumbeus	0.273	0.238
*Carcharhinus spp**	0.427	0.270
Galeocerdo cuvier	0.376	0.331
Carcharhinus limbatus/tilstoni	1	0.964
Rhizoprionodon acutus	1	0.736

Table 3. Summary of the lengths of target species measured on pelagic stereo-BRUVs and caught on scientific longline surveys. Maximum (Max), minimum (Min) and mean fork length (FL) are shown in millimetres.

	Max FL (mm)		**Min FL** (mm)		**Mean FL** (mm)	
Species	BRUVs	Longline	BRUVs	Longline	BRUVs	Longline
Family Carcharhinidae	2937	2870	587	702	1348	1367
Carcharhinus plumbeus	1386	1600	587	730	1089	1280
*Carcharhinus spp**	1855	2110	1157	1534	1534	1627
Galeocerdo cuvier	2937	2870	1285	930	2028	1823

FIGURES:

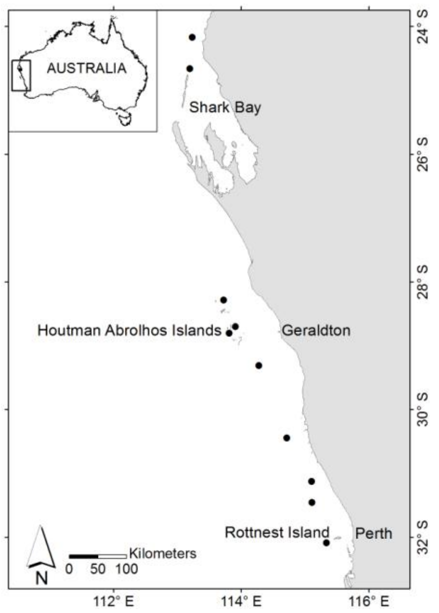

Fig. 1. Location of study sites along the coast of Western Australia.

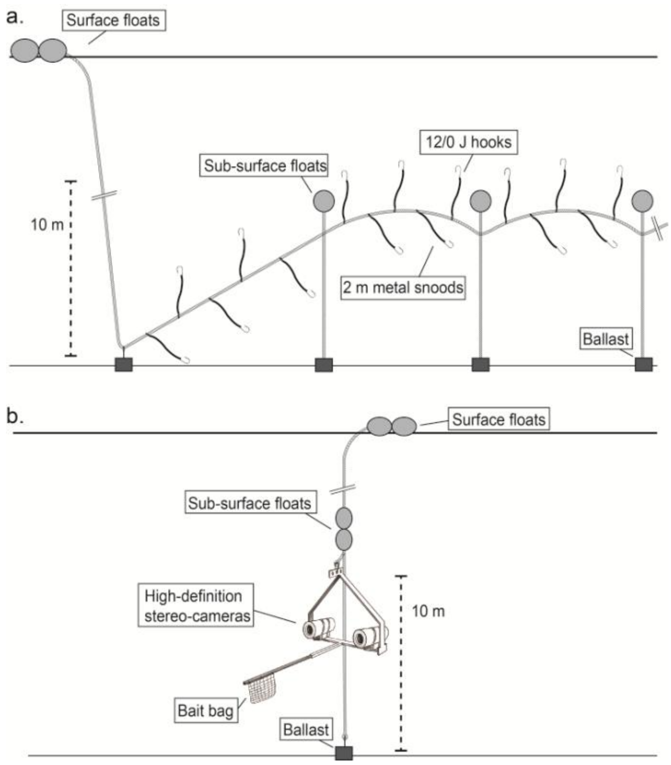

Fig. 2. Deployment design of the (a) scientific longline shots and (b) pelagic stereo-BRUVs used to sample requiem sharks.

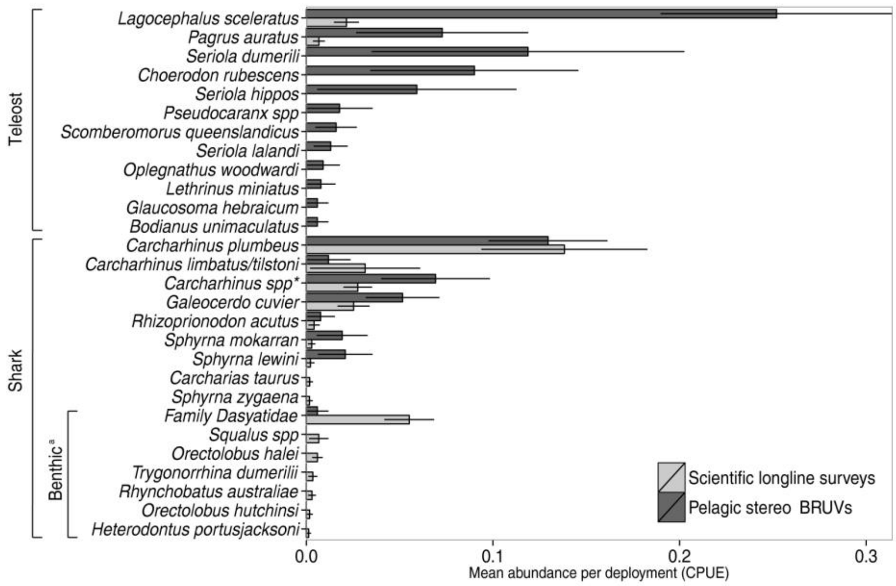

Fig. 3. Mean relative abundance of fish species sampled using scientific longline surveys and pelagic stereo-BRUVs. Catch per unit of effort (CPUE) is shown as catch per hour for 10 hooks (CPUE10) in longline samples and as MaxN per hour in stereo-BRUVs. [a] Benthic sharks were caught in longlines due to the deployment design setting of a proportion of hooks near the bottom.

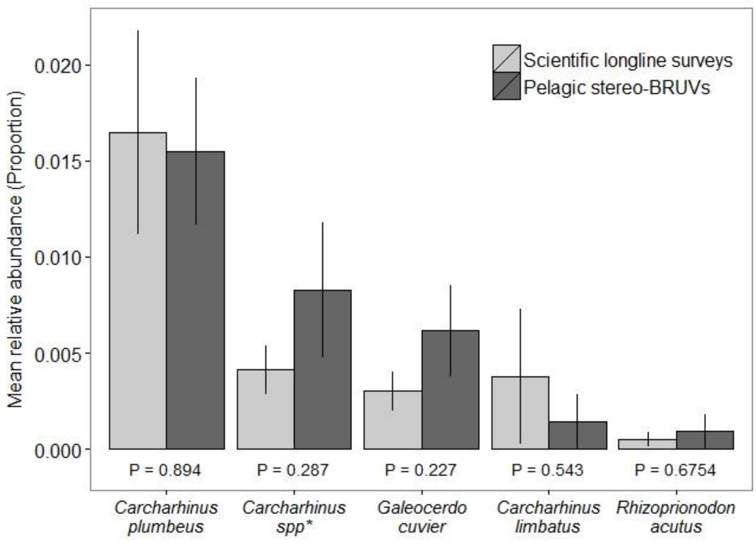

Fig. 4. Mean species proportion of target species sampled using scientific longline surveys and pelagic stereo-BRUVs. P-values show non-significant differences between sampling methods.

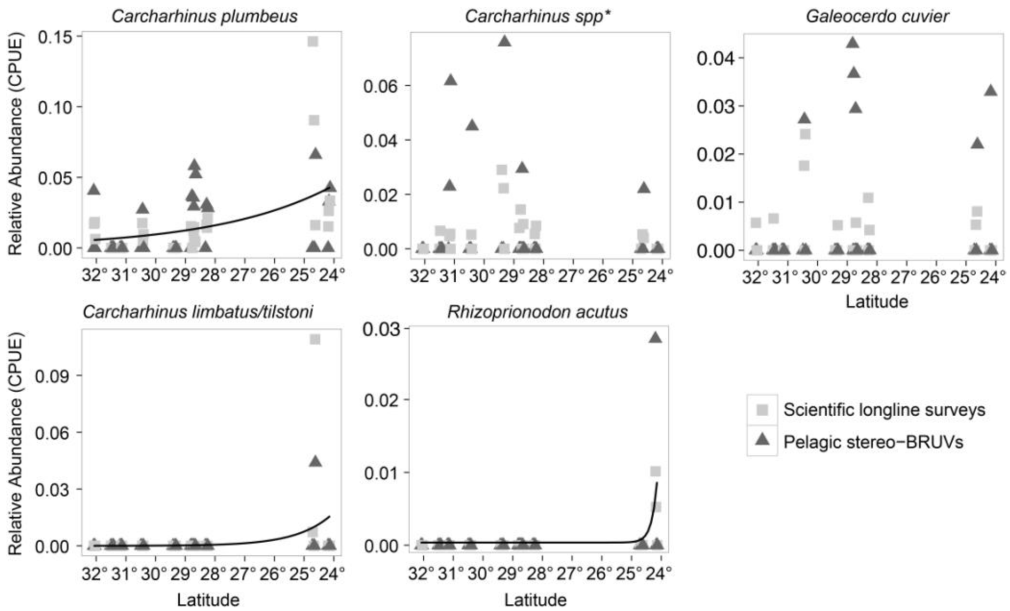

Fig. 5. Relative abundance (CPUE) of target species along a latitudinal gradient (32° - 24° S) sampled using scientific longline surveys and pelagic stereo-BRUVs. Trendlines illustrate the ANCOVA result.

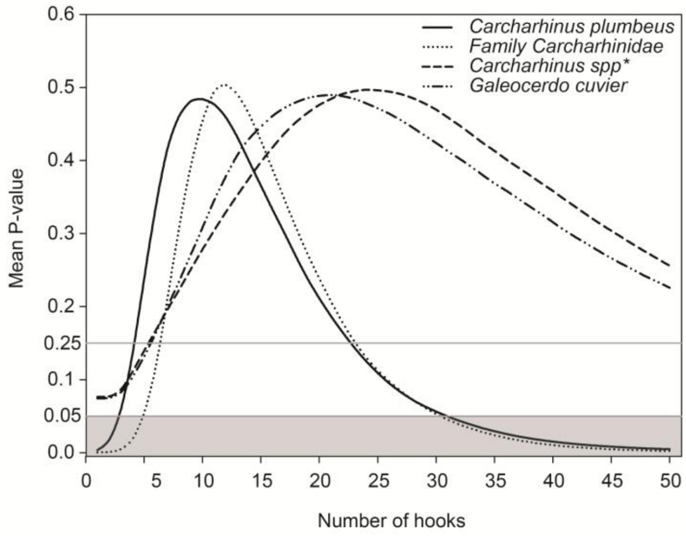

Fig. 6. Equivalence of sampling effort required to estimate relative abundance of requiem sharks. Plot shows mean p-values from one-way PERMANOVAs testing the differences between pelagic stereo-BRUVs (MaxN per hour) and scientific longline surveys (catch*h^{-1} *$hook^{-1}$) across different levels of sampling effort (number of hooks). Values in the shaded area ($P < 0.05$) are statistically significant. Grey line is shown for reference as the general pooling cut-off ($P > 0.25$).

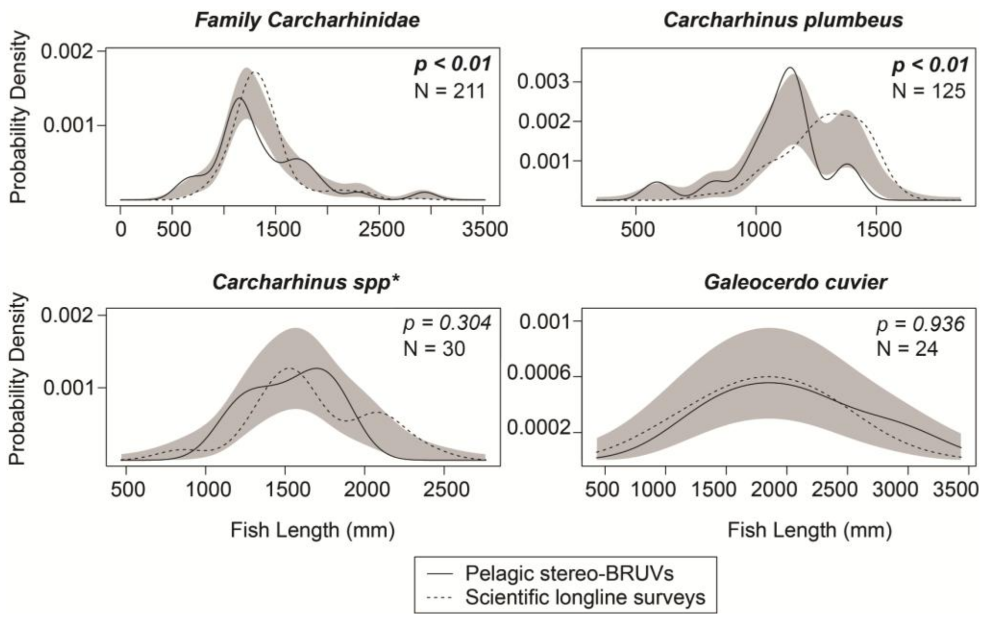

Fig. 7. Comparison of kernel density estimate (KDE) probability density functions for the length distributions of requiem shark species caught by pelagic stereo-BRUVs and scientific longline surveys. Grey bands represent one standard error either side of the null model of no difference between the KDEs for each method.