



Cost-efficient sampling of fish assemblages: comparison of baited video stations and diver video transects

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ABSTRACT: Baited remote underwater stereo-video (stereo-BRUV) stations and diver operated stereo-video (stereo-DOV) transects are increasingly used to sample both tropical and temperate fish assemblages. Compared to *in situ* visual census methods, the use of stereo-video reduces inter-observer variability, improves definition of the sample unit area, increases accuracy of fish length estimates and provides a permanent record of the assemblage that can be validated where required or independently reanalysed. Previous studies have suggested that stereo-BRUV collects representative data on both carnivorous and herbivorous species and can be more cost-efficient than diver-based survey methods. This study compares estimates of common fish assemblage metrics obtained with stereo-BRUV stations and stereo-DOV transects across 3 biogeographic regions, and uses a cost-optimization procedure to compare the efficiency of these 2 methods. Stereo-BRUV stations were found to sample greater species richness and obtain greater estimates of relative biomass of generalist carnivores, but no differences occurred in the biomass of herbivores sampled by the 2 techniques. Stereo-BRUV stations generally obtained estimates of assemblage metrics with less variance, resulting in greater power to detect spatial and temporal changes in the fish assemblage metrics. Cost-benefit analyses found that stereo-BRUV was generally more time efficient than stereo-DOV transects in terms of smaller standard error around the mean of the various metrics considered. However, across the 3 biogeographic regions sampled there was considerable variation in the magnitude of these differences. Results suggest that stereo-BRUV stations are, in general, a more cost-effective method for monitoring fish assemblages than stereo-DOV transects.

KEY WORDS: Cost-benefit · Power to detect change · Biogeography · Baited remote underwater stereo-video · Diver operated stereo-video

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INTRODUCTION

An important consideration in designing any robust ecological study is the choice of sampling method (Thomas 1996, Rotherham et al. 2007). Different sampling methods may result in different estimates of a population's mean and variance (Andrew & Mapstone 1987). This will in turn have important consequences for the power of any sampling program to detect change in the variable of interest (Winer 1991). To maximise the power of a monitoring program to detect change over time, a sampling methodology that max-

imises the mean and minimises variance due to sampling error should be chosen (Underwood & Chapman 2003). Within large-scale studies or monitoring programs, various scales of nested sites allow the investigation of spatial variation and provide a test of differences between regions over and above the variation among sites within a region. Therefore, an important consideration in designing any large-scale study is the benefit of additional replication, either at the lowest level of a design or at the level of sites (Underwood 1981). Cost-benefit procedures can be used to optimise the distribution of effort based on variance among

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replicates and sites from pilot study data and, therefore, can also be used to evaluate the cost-effectiveness of different sampling methods.

The complete sampling of reef fish communities in shallow waters is only possible using destructive methods. Indiscriminate methods such as dynamite have historically been used (Stephan 1904); however, the use of fish toxins such as rotenone (Krumholz 1948) have allowed more discrete and quantitative samples of the fish assemblage to be collected from complex habitats (Robertson & Smith-Vaniz 2008). Recent advances in diving technology have allowed these methods to be used to depths of 150 m, resulting in the description of large numbers of new cryptic species and observations of higher rates of endemism in deeper compared to shallow reefs (Pyle 2000). However, for most large-scale studies, sampling the complete fish assemblage is likely unnecessary (Clarke & Warwick 1998) and destructive methods bias future samples obtained from the same locality and can compromise management objectives (e.g. inside marine reserves, Willis et al. 2000).

A range of underwater visual census methods have been used to non-destructively sample fish communities (Harmelin-Vivien et al. 1985, McCormick & Choat 1987, Halford & Thompson 1994). However, specific sources of error in diver-based visual census methods have been identified, including fish behaviour (Cole 1994, Watson & Harvey 2007), inter-observer variability in species identification (Lincoln Smith 1988, Legg & Nagy 2006) and estimates of abundance (Sale & Sharp 1983, Lincoln Smith 1988) and length and range (Harvey et al. 2004). Apart from fish behaviour, these problems can be minimised by using the same observers or by implementing consistent training programs (Sale & Sharp 1983). However, during long-term studies it is possible that biases or additional variability will be introduced. Using video techniques with diver-swum transects provides a permanent record of the assemblage that can be validated where required or independently reanalysed.

Various studies have suggested that some species of fish may either be attracted to or repelled from divers or snorkelers (Cole 1994, Cole et al. 2007, Watson & Harvey 2007), including the large carnivorous species that may be of interest to the objectives of long-term monitoring programs (Kulbicki 1998, Willis et al. 2000). The behaviour of such large carnivorous species has been observed to change across small spatial scales (e.g. inside and outside a marine reserve, Cole 1994). This behavioural response means that, although diver surveys may be conducted with a standardised sample unit size (e.g. transect size, McCormick & Choat 1987), the abundance estimates will be relative to the behaviour of the fish within a particular area (Willis et al. 2000).

An additional limitation of all diver-based methods is the depth and frequency of dives that can be undertaken. Mixed gas technologies can allow divers to use visual census methods at greater depth (<150 m, Pyle 2000); however, for frequent sampling in long-term studies these technologies are normally prohibitive from a cost and occupational health and safety perspective.

Remote video stations, referred to thus as they are deployed without divers, are increasingly used under an array of configurations. Bait has previously been used to increase the number of fish sampled by seine nets (Lenanton et al. 1982) and traps (Munro 1974), and for this reason it has also been used with remote video stations. Watson et al. (2005) and Harvey et al. (2007) compared baited and unbaited remote video stations and found that the addition of bait increased the abundance of carnivorous species but did not decrease the abundance of herbivores. Downward-facing baited video stations have been used to sample in a range of depths (Sainte-Marie & Hargrave 1987), and have been found to obtain estimates of the spatial distribution of carnivorous species similar to those obtained by experimental fishing (Willis et al. 2000). There is some suggestion that these methods remove the behavioural biases found with diver surveys (Willis et al. 2000); however, there will undoubtedly be additional biases associated with the addition of bait. Horizontally facing baited or unbaited video stations have also been found to sample a wide range of species (Francour et al. 1999, Cappo et al. 2004) and to sample tropical assemblages better than downward-facing cameras (Langlois et al. 2006). Stereo-video techniques are particularly useful for horizontally facing baited video stations (Harvey et al. 2007, Stobart et al. 2007, Shortis et al. 2009) as they can obtain accurate estimates of fish length and define the area of the sampling unit by measurement of the distance to the cameras (Harvey et al. 2010).

A great advantage of methods based on remote stations is that they can be deployed in a range of depths and multiple systems can be used simultaneously to greatly improve efficiency in the field (Watson & Harvey 2007). However, traditional diver-based visual methods tend to obtain greater species richness than either horizontally facing baited video stations or diver-operated video methods, due to the advantages of the human eye (Le Grand 1968) over video technologies (Tessier et al. 2005). Previous comparisons have also found that diver-based surveys tend to sample a smaller size structure of particular species than remote video stations (Watson et al. in press). Several studies have suggested that baited remote underwater stereo-video (stereo-BRUV) methods sample, on average, a greater number of individual reef fish species and

greater abundance and/or biomass of generalist carnivore species than diver-operated stereo-video (stereo-DOV) methods (Harvey et al. 2002, Watson et al. 2005). However, it has also been suggested that diver-swum transects sample, on average, a greater abundance and/or biomass of herbivorous fish species (Kulbicki 1998, Willis et al. 2003). A comparison of visual point counts by divers and unbaited video stations by Francour et al. (1999) found video stations to be more cost-efficient in terms of total time spent in the field and in the laboratory.

The objective of the present study was to compare common fish assemblage metrics obtained using the 2 stereo-video methods and to investigate if either method had greater statistical power or was more cost-efficient in detecting change in assemblage metrics. In particular, we wanted to investigate whether there were consistent differences between the 2 methods across 3 biogeographic regions, as both of these methods are being used with increasing regularity in Western Australia and around the world.

The data presented here were not collected specifically to address the following hypotheses, but were collected by studies focused on local assessments of reef fish assemblage structure using stereo-BRUV and stereo-DOV methods. Both methods use stereo-video techniques to provide accurate estimates of individual fish length (Harvey et al. 2002) and define the area of the sample unit (Harvey et al. 2004). For the present

study, field sites within Western Australia included the tropical Ningaloo Reef, the subtropical Houtman Abrolhos Islands and the temperate Capes region (Fig. 1a). By comparing fish assemblages sampled by stereo-DOV and stereo-BRUV methods across 3 biogeographic regions we will be able to informally test the generality of any differences between these methods. Within each of the 3 biogeographic regions the present study investigated the following hypotheses: (1) estimates of reef fish assemblage structure will have lower variance using stereo-BRUV compared to stereo-DOV methods; (2) stereo-BRUV methods sample a greater average number of individual species; and (3) for the biomass of generalist carnivore species, stereo-BRUV methods will have greater power to detect any change and greater cost-efficiency than stereo-DOV methods. In contrast, we also predicted that: (4) for estimating the biomass of herbivorous fish species, stereo-DOV methods will sample greater average biomass with less variance and, therefore, be more cost-efficient and have greater power to detect change for this functional group.

MATERIALS AND METHODS

Sampling design. Within each region the sampling design was made orthogonal to the 2 sampling methods to be compared. The design of the studies within each region differed, reflecting the known environ-

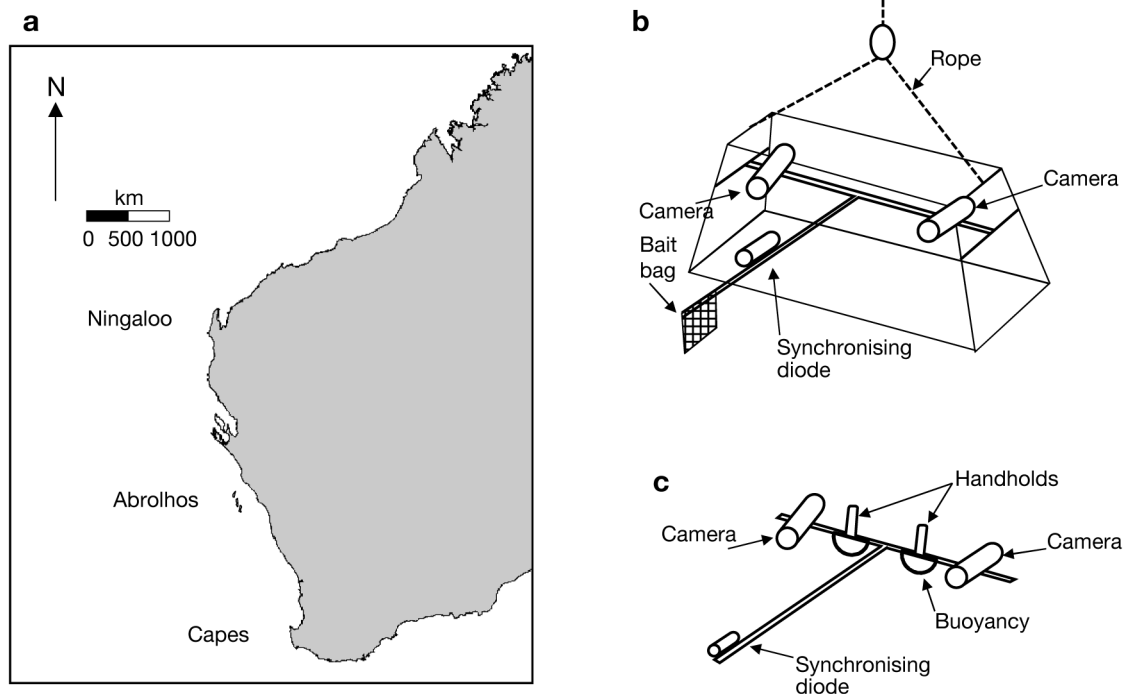


Fig. 1. (a) Western Australia, showing the 3 regions that were sampled with stereo-BRUV and stereo-DOV methods. Stereo-video systems for sampling reef fish: (b) baited remote underwater stereo-video (stereo-BRUV) and (c) diver-operated stereo-video (stereo-DOV)

mental gradients and particular objectives of the individual investigations. Occasionally problems occurred with the stereo-video methods in a sample, which meant that it was not possible to obtain length measurements of fish, resulting in the sample being discarded.

At Ningaloo Reef (Ningaloo), 2 random locations adjacent to 2 established no-take marine reserves were sampled. Within each location, 6 sites were randomly chosen to represent the diversity of habitat types found within each location. Six replicate 50 × 5 m stereo-DOV transects and 6 replicate stereo-BRUV deployments were analysed from each site in 1 to 10 m water depth. Due to problems with the stereo-systems, 1 stereo-BRUV replicate and 2 stereo-DOV transects were missing from the data set.

At the Houtman Abrolhos Islands (Abrolhos), a location adjacent to a partial-take marine protected area at each of the 3 island groups was sampled (Pelsaert, Easter and Wallabi). These 3 locations were considered as a fixed factor as there is a known gradient in the fish communities between the island groups (Watson & Harvey 2009). Within each location, 3 sites were randomly chosen and stereo-DOV transects were conducted along the same reef slope as stereo-BRUV deployments, ensuring similar habitats along the reef edge were sampled. Five replicate 100 × 5 m stereo-DOV transects and 5 replicate stereo-BRUV deployments were analysed from each site. Due to problems with the stereo systems, 1 stereo-BRUV replicate and 4 of the 45 stereo-DOV transects were missing from the data set. All surveys were conducted on the same coral reef slopes in 8 to 12 m water depth.

In the Capes region (the Capes), 3 random locations were sampled within the proposed no-take and comparable fished areas. At each of these locations, 3 random sites were sampled. Nine replicate 25 × 5 m stereo-DOV transects and 9 replicate stereo-BRUV deployments were analysed from each site with no missing samples. All surveys were conducted in comparable rocky reef habitats in 8 to 18 m water depth.

Stereo-BRUV. The stereo-BRUV method used in the present study is the same as that used by Harvey et al. (2002) and Watson et al. (2005, 2007). Detailed information on the design and photogrammetric specifics are presented in Harvey & Shortis (1996, 1998). Stereo-BRUV systems were comprised of 2 SONY HC 15E video cameras mounted 0.7 m apart on a base bar inwardly converged at 8 degrees to gain an optimized field of view with visibility of 7 m distance (Harvey & Shortis 1996; Fig. 1b). A synchronising diode and bait basket was positioned in front of the cameras (Fig. 1b). Each system was deployed by boat and left to film on the sea floor for a period of 1 h. With multiple systems in use, a single stereo-BRUV could be deployed at one

site, followed by one at a second site and so on, maximising sampling efficiency. Previous research in temperate regions has found that >36 min is required to obtain measures of the majority of fish species, and that 60 min is advisable to include targeted fish species (Watson et al. 2005). Systems were baited with 800 g of pilchard *Sardinops sagax* in a plastic-coated wire mesh basket, suspended 1.2 m in front of the 2 cameras. The pilchards were crushed to maximise dispersal of the fish oil. Adjacent replicate stereo-BRUV deployments at the Capes, Abrolhos and Ningaloo were separated by at least 250 m to avoid overlap of bait plumes and reduce the likelihood of fish moving between stereo-BRUV stations within the sampling period.

Stereo-DOV. The stereo-DOV method used in the present study is the same as that used by Harman et al. (2003) and Watson et al. (2005). The stereo-DOV system comprised 2 SONY TRV900E video cameras which, similarly to the stereo-BRUVs, were mounted horizontally 0.7 m apart on a base bar inwardly converged at 8 degrees (Fig. 1c). The stereo-DOV system was equipped with a synchronising diode mounted in front of the cameras, and floats to achieve neutral buoyancy (Fig. 1c). Stereo-DOV was conducted by 2 SCUBA divers with one operating the stereo-video system and the other measuring the distance swum with a chainman cotton counter (bio-degradable cotton). SCUBA divers swam at a slow speed ($\sim 3 \text{ m s}^{-1}$) at a distance of approximately 30 cm above the substrate with the cameras facing slightly downward. In all instances replicate transects were separated from the previous by at least 15 m.

Costs. The costs associated with conducting sampling using the 2 stereo-video methods were calculated for each of the 3 regions from field records during 2006–2007. For each method, the costs were classified as costs per site or cost per replicate and expressed in hours of staff time. Mobilisation, vessel costs, equipment insurance and consumables were not included in the cost-optimization procedure as they were comparable between the methods. By using staff time (h) for the cost–benefit analysis the results can be more easily translated to different locations. The estimate of cost per site was calculated for 1 vessel deploying either 2 dive teams (stereo-DOV) or 8 video systems (stereo-BRUV) simultaneously and were calculated to be 299 staff hours for stereo-DOV and 89 staff hours for stereo-BRUV. Video analysis was used to estimate the cost per replicate sample within a site, this included staff time to convert video images and produce estimates of abundance and length for each fish taxa observed using the software described below (see Table 2). The time to analyse the video samples differed between each region due to differences in the species richness and overall number of fish. These esti-

mates are likely to decrease with increasing developments of stereo-video analysis software.

Video analysis. For both stereo-BRUV and stereo-DOV samples, the analysis of the data was facilitated through a custom database (BRUVS1.5.mdb© 2006 Australian Institute of Marine Science). This database enabled us to manage data collected from the field operations and tape readings, capture the timing of events and reference images of the seafloor and fish in the field of view. For stereo-BRUV we recorded the maximum number of any one species seen at one time during the recording (N_{\max}). Estimates of N_{\max} are considered conservative, particularly in areas where fish occur in high densities (Cappo et al. 2003, 2007). For each stereo-DOV, every individual observed on the transect was counted and identified to species level where possible. Individual fish that entered the transect whilst the survey was being conducted were also included in the sample.

The program PhotoMeasure (www.seagis.com.au) was then used to make length measurements from stereo-video images (snout to fork length [FL]). To avoid making repeated measurements of the same individuals with the stereo-BRUV samples, measures of length were made at the time of N_{\max} . To ensure good measurement accuracy and precision, as well as a standardized sampling unit, all measures of fish length for stereo-BRUV samples were limited to within a maximum distance of 5 m from the cameras (Harvey et al. 2002), resulting in a sample unit area of 25.5 m². The software calculates both distance from the cameras and length at the same time; using this information, measurements and counts of abundance of species further than 5 m from the cameras were discarded.

For stereo-DOV transects, all fish observed were measured and the distance in front of and to the left and right of the diver were obtained simultaneously, enabling standardisation of the area surveyed. Individuals further than 7 m in front of or 2.5 m to the left or right of the stereo-DOV system were not counted or measured.

For each stereo-BRUV sample, lengths of individuals of each species were converted to weight using length-weight relationships obtained from Fishbase (Froese & Pauly 2009) and summed for each species. Where a species-specific relationship was not available, that of a similar congener was used. These summed weights are considered to be a relative estimate of biomass, as although the sample unit area of the stereo-BRUV systems has been standardised, different fish species may have been attracted from varying distances into the sample unit of the stereo-BRUV by the bait. In the 'Results' section, the relative biomass estimates generated from the stereo-BRUV systems will be referred to simply as biomass estimates.

For each stereo-DOV sample, the lengths of individuals of each species were converted to weight as above and summed for each species for each transect providing an estimate of the biomass over the area of each transect. A single species, *Chromis westaustralis*, was excluded from length analysis as measurements of these individuals from stereo-DOV footage were difficult due to their small size and schooling behaviour.

Statistical analyses. Three univariate variables were of particular interest: the species richness, the average biomass of generalist carnivores and the average biomass of herbivores. These variables were analysed using univariate ANOVA using the program GMAV5 (Underwood et al. 2002). Each variable was standardised to z-scores using the mean and standard deviation to account for any difference in sample unit size between the methods and regions. All ANOVA analyses were preceded by Cochran's test for homogeneity of variance (see Underwood 1981). Where the test showed significant heterogeneity, variables were transformed to $x' = \ln(x + 1)$. ANOVAs were followed by a *posteriori* Student-Newman-Keuls (SNK) tests on appropriate terms of the model found to be significant with $p < 0.05$. Mean and standard deviation plots used the unstandardised density estimates obtained in each region; for stereo-DOV this was 250 m² at Ningaloo, 500 m² at Abrolhos and 125 m² at the Capes. Stereo-BRUV density estimates are relative given the attraction of bait and therefore not expressed per meter, but were comparable across all regions.

The power to detect change in these 3 univariate variables was investigated using a simple 1-way ANOVA model with 2 levels, before and after. The power of each method to detect a change of 25 and 50% was estimated using the mean and variance estimates of the univariate variables for each region pooled for sites and locations. Non-central *F* probabilities were calculated for each comparison using the program G*Power (Faul et al. 2007); these were used to estimate the power of each method to detect change with increasing sample size within each factor. The contribution of the nested sites and locations within each region to the power of any future monitoring program to detect change was not calculated, as it is computationally impossible to calculate power for mixed models (Winer 1991).

The logistics of any monitoring program, including the replication of nested sites and individual replicates for the detection of change in these univariate variables over time was investigated using a cost-benefit optimization, as described by Underwood (1981). The staff time (h) associated with each replicate and site for stereo-DOV and stereo-BRUV methods were estimated from field records during 2006–2007 for the 3 regions, and are given in Table 1.

Table 1. Estimates of analysis time per replicate for diver-operated stereo-video (stereo-DOV) and baited remote underwater stereo-video (stereo-BRUV) for each of the 3 regions from field records during 2006–2007. All costs (per replicate) are given as staff time (h)

Region	Stereo-BRUV	Stereo-DOV
Ningaloo	3	2.5
Abrolhos	2.5	1.25
Capes	1.75	0.4

Species-specific differences between the 2 methods were visualised by plotting the standardised proportional biomass for each species. These standardised values can be considered as proportions of the total biomass sampled by each method. A one-to-one line was used to indicate where species would occur if they had been sampled in equal proportions by stereo-DOV and stereo-BRUV methods.

RESULTS

Species richness

In the ANOVAs for the comparative studies at Ningaloo (Table A1 in Appendix 1), Abrolhos (Table A2) and the Capes (Table A3), there was increasing support for the hypothesis that stereo-BRUV methods would, on average, record more species than stereo-DOV. At Ningaloo there was a significant interaction of Method and Site ($F_{8,80} = 1.56$, $p < 0.01$; Table A1) and no consistent differences were seen in the average number of species sampled by the 2 methods (Fig. 2). However, at Abrolhos, there was a strong effect of Method ($F_{1,6} = 10.88$, $p < 0.01$) and Site ($F_{6,72} = 6.28$, $p < 0.001$; Table A2), but no interaction. This pattern can be clearly seen in the non-standardised data shown in Fig. 2, but the differences are not as great as those found at the Capes. A strong effect was seen at the Capes, with a significant effect of Method ($F_{1,2} = 84.24$, $p < 0.01$; Table A3) and no significant interactions. Again this pattern can be clearly seen in the non-standardised data shown in Fig. 2.

The power of each method to detect significant changes in species richness was found to be very similar between stereo-BRUV and stereo-DOV at both Ningaloo and Abrolhos (Fig. 2). However, at the Capes, where there was a larger difference between the species richness sampled by each method, stereo-BRUV was found to have greater power than stereo-DOV for the same level of replication (Table 2, Fig. 2). Cost-benefit optimization found that stereo-BRUV methods were consistently more cost-effective for detecting

change in species richness than stereo-DOV methods across all bioregions (Table 3).

To further investigate the species model, we compared the total number of fish taxa sampled by the stereo-BRUV and stereo-DOV methods within each region (Table 4). There was a trend of increasing percentage of unique taxa sampled by stereo-BRUV from Ningaloo (41%) to the Capes (67%), and an inverse trend of decreasing percentage of taxa shared between the methods. Despite the large change in the number of taxa sampled by the stereo-DOV from Ningaloo (103 taxa) to the Capes (29 taxa), it is also interesting to note that the percentage of unique taxa sampled by this method was relatively constant between the regions (Ningaloo 18%, Abrolhos 26%, the Capes 17%).

Herbivores

These analyses gave no support to the hypothesis that stereo-DOV methods would, on average, record greater biomass of herbivores than stereo-BRUV. The only significant terms in the ANOVA models were a Site effect at both Ningaloo ($F_{8,80} = 1.08$, $p < 0.01$; Table A1) and Abrolhos ($F_{6,72} = 2.52$, $p < 0.05$; Table A2). There is some evidence that stereo-DOV sampled a greater biomass of herbivores (Fig. 3), but these differences were not significant after standardisation between the methods.

There was also no difference in the power of stereo-BRUV and stereo-DOV methods to detect any change in the biomass of herbivores at Ningaloo and Abrolhos. However, at the Capes the power of stereo-DOV to detect change was marginally greater than stereo-BRUV, although the power was very low except at very high levels of replication (Fig. 3).

The cost-benefit analyses found that stereo-BRUV methods would be more cost-efficient at detecting change in the biomass of herbivores at Ningaloo and Abrolhos, given variance between sites was greater using stereo-DOV than stereo-BRUV methods. This was not the case at the Capes, where there was greater among-site variation in the estimates of herbivore biomass using stereo-BRUV methods, indicating that a large number of sites should be sampled. At the Capes, cost-benefit optimization suggested that stereo-DOV methods would be more cost-efficient for the smallest effect size examined (10%), despite the very large number of individual replicates required (Table 3). However, at larger effect sizes stereo-BRUV methods were found to be more cost-efficient even though a larger number of sites were required to be sampled than when using the stereo-DOV methods.

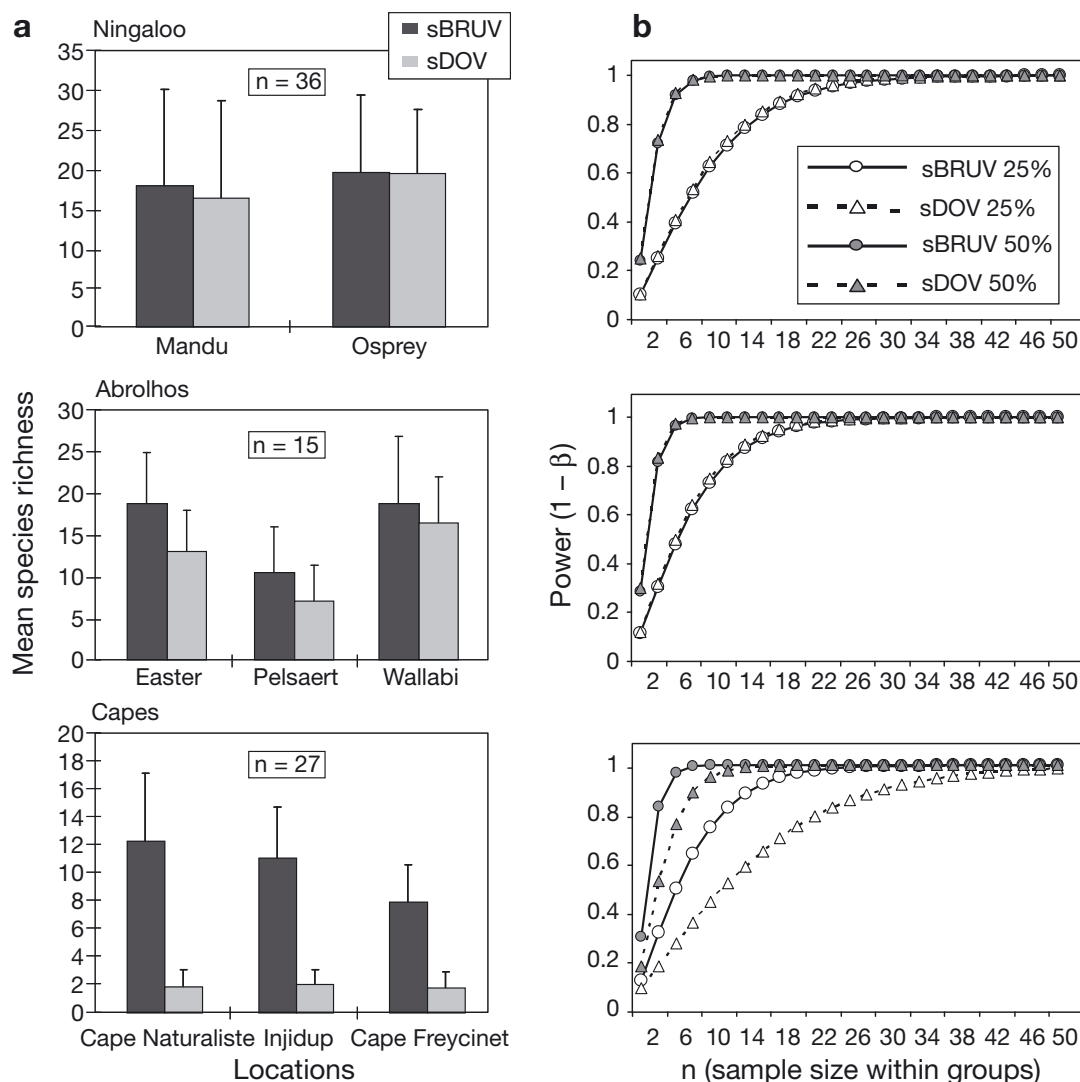


Fig. 2. Species richness. (a) Mean (+1 SD) number of species and (b) power to detect a change of 25 or 50% in the number of species at Ningaloo Reef, the Abrolhos Islands and the Capes region sampled by the stereo-BRUV (sBRUV) and stereo-DOV (sDOV) methods. For (a) absolute differences are shown for each location sampled within the 3 regions (sites and replicates pooled), and for (b), power was estimated using overall mean and variance estimates for each region. For stereo-DOV, estimates of species richness are per 250 m² at Ningaloo, 500 m² at the Abrolhos Islands and 125 m² at the Capes region, whilst stereo-BRUV estimates are relative given the attraction of bait and, therefore, are not expressed per meter, but are comparable across all regions

Generalist carnivores

There was increasing support for the hypothesis that stereo-BRUV methods would, on average, record greater biomass of generalist carnivores than stereo-DOV from Ningaloo (Table A1), to Abrolhos (Table A2) to the Capes (Table A3). At Ningaloo, no support was found for the generalist carnivore model. There were no significant terms in the ANOVA model (Table A1) and no consistent differences can be seen in the average number of species sampled by the 2 methods (Fig. 2). However, at Abrolhos there was a strong effect of Method ($F_{1,6} = 19.35$, $p < 0.01$) and Island Group

($F_{2,6} = 7.67$, $p < 0.05$; Table A2). As there were no significant interactions, the effect of Method was consistent at each Island Group. This pattern can be seen in the raw data shown in Fig. 4, but it appears that stereo-DOV methods are more likely to sample generalist carnivores here than at the Capes. Finally, a strong effect was again seen at the Capes with a significant effect of Method ($F_{1,2} = 97.16$, $p < 0.01$; Table A3), but there were no significant interactions; this pattern can be clearly seen in the non-standardised data shown in Fig. 4.

Stereo-BRUV methods had consistently more statistical power (Fig. 4) and were more cost-effective in detecting changes (Table 3) at Ningaloo, Abrolhos and

Table 2. Summary of which method was found to have the greatest the power to detect change in species richness, biomass of herbivores, biomass of generalist carnivores and total biomass of all fish at Ningaloo Reef, the Houtman Abrolhos Islands and the Capes region. sBRUV: stereo-BRUV

Parameter	Region		
	Ningaloo	Abrolhos	Capes
Species richness	Equal	Equal	sBRUV
Herbivores	Equal	Equal	sBRUV
Generalist carnivores	Equal	sBRUV	sBRUV
Total biomass	sBRUV	sBRUV	sBRUV

the Capes. Despite the lack of significant differences in the absolute values at Ningaloo, the lower levels of among-site variation observed with the stereo-BRUV methods resulted in a more powerful and cost-effective sampling program.

Species-specific differences between methods

Plots of the biomass of each fish species sampled, standardised between methods, allow the species-specific differences to be visualised (Fig. 5). Despite the lack of evidence for the generalist carnivore model at Ningaloo, there appears to be a strong association of

these species with the stereo-BRUV method (Fig. 5). At Ningaloo it is also interesting to note that the spangled emperor *Lethrinus nebulosus* appeared to be sampled in the same proportions by both methods, whereas the parrotfish *Scarus schlegeli* was more common in the stereo-DOV samples.

At Abrolhos, as we would expect given the differences in the biomass of generalist carnivores demonstrated by ANOVA tests, species such as the pink snapper *Pagrus auratus*, the spangled emperor *Lethrinus nebulosus* and the coral trout *Plectropomus leopardus* were sampled in greater proportions with stereo-BRUV compared to stereo-DOV methods (Fig. 5). The parrotfishes *Scarus schlegeli* and *Chlorurus sordidus* and the drummer *Kyphosus cornelii* were sampled in greater proportions with the stereo-DOV. It is also interesting to note that the baldchin groper *Choerodon rubescens* was sampled in relatively equal proportions by the 2 methods.

Within the 3 locations sampled at the Capes, the stereo-BRUV method sampled proportionally much greater biomass of most species than stereo-DOV, with the exception of McCulloch's scalyfin *Parma mccullochi* (Fig. 5). Greater biomass of species such as *Pagrus auratus* and the western king wrasse *Coris auricularis* were sampled by stereo-BRUV. The rare blue groper *Achoerodus gouldii* was also sampled in greater proportions by stereo-BRUV.

Table 3. Cost-benefit optimization of monitoring programs using either stereo-BRUV (sBRUV) or stereo-DOV (sDOV) methods within the 3 regions, for species richness, biomass of herbivores and biomass of generalist carnivores. For logistical reasons, the number of replicates for stereo-DOV and stereo-BRUV methods was limited to 20 samples; however, the number of sites was set by the optimization procedure and occasionally this procedure suggested more than 20 samples per site. The most cost-efficient sampling method for each region and each indicator are shown in **bold**. *: different methods were cost-effective with different numbers of sites

Indicator	Region	Method	Replicates	Sites to detect change of:			Cost (h) per survey to detect a change of:		
				10%	25%	50%	10%	25%	50%
Richness	Ningaloo	sBRUV	6	23	4	1	2065	374	107
		sDOV	9	26	5	2	7797	1518	621
	Abrolhos	sBRUV	7	13	2	1	1175	196	107
		sDOV	20	18	3	1	5407	922	324
	Capes	sBRUV	20	3	1	1	302	124	124
		sDOV	>20	6	1	1	1802	307	307
Herbivores	Ningaloo	sBRUV	7	6	1	1	555	110	110
		sDOV	14	7	2	1	2128	633	334
	Abrolhos	sBRUV	>20	10	2	1	920	208	119
		sDOV	12	10	2	1	3015	623	324
	Capes	sBRUV*	>20	27	5	2	2438	480	213
		sDOV*	>20	5	1	1	1503	307	307
Carnivores	Ningaloo	sBRUV	>20	1	1	1	185	185	185
		sDOV	14	4	1	1	1231	334	334
	Abrolhos	sBRUV	>10	1	1	1	122	122	122
		sDOV	>20	3	1	1	922	324	324
	Capes	sBRUV	>20	1	1	1	175	175	175
		sDOV	>20	22	4	1	6690	1308	411

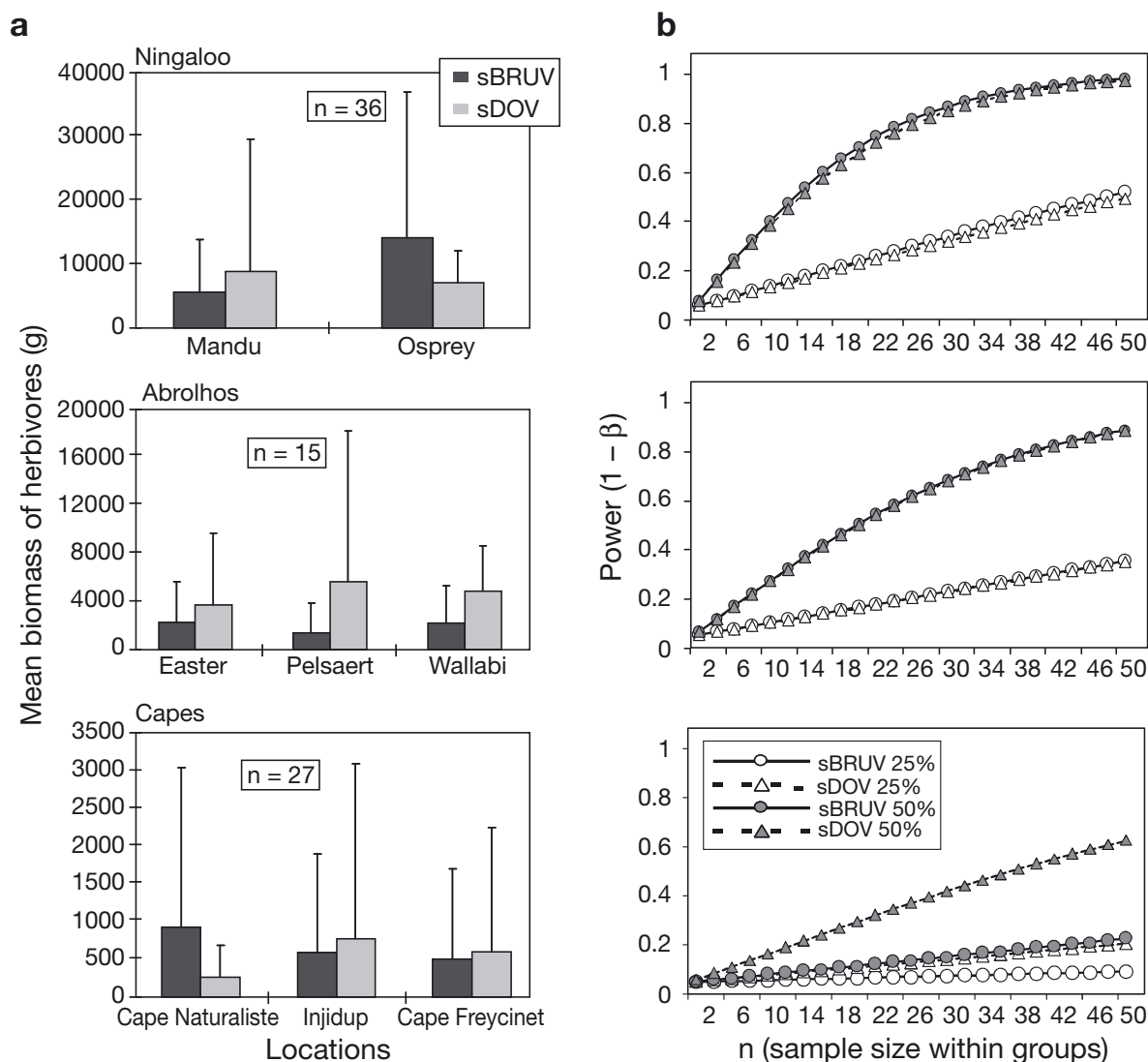


Fig. 3. Biomass of herbivores. (a) Mean (+1 SD) biomass and (b) power to detect a change of 25 or 50% in the biomass of herbivores at Ningaloo Reef, the Arolhos Islands and the Capes region sampled by the stereo-BRUV (sBRUV) and stereo-DOV (sDOV) methods. See Fig. 2 for details on the units and standardisation between the regions

Table 4. Summary of the number of fish taxa sampled by the stereo-DOV and stereo-BRUV methods within each region. The total number of taxa sampled by stereo-DOV and stereo-BRUV is shown, with the percentage unique to each method in brackets. The combined total of taxa and the number of taxa shared between the 2 methods is also shown

Region	No. taxa		
	Stereo-BRUV (% unique)	Combined (% shared)	Stereo-DOV (% unique)
Ningaloo	143 (41)	162 (52)	103 (18)
Arolhos	111 (51)	133 (41)	73 (26)
Capes	73 (67)	78 (24)	29 (17)

DISCUSSION

This simple comparative study has provided useful insights into how 2 different sampling methods can obtain comparable data in certain regions, whilst providing quite different estimates of the mean and variance of assemblage metrics within other regions. These differences resulted in the 2 methods having contrasting levels of statistical power to detect change in assemblage metrics in particular regions. Replication of samples and nested sites are particular to the 2 methods, and stereo-BRUV methods were the most cost-efficient overall in terms of staff time. Strong support was found for all of the hypotheses posed, with the

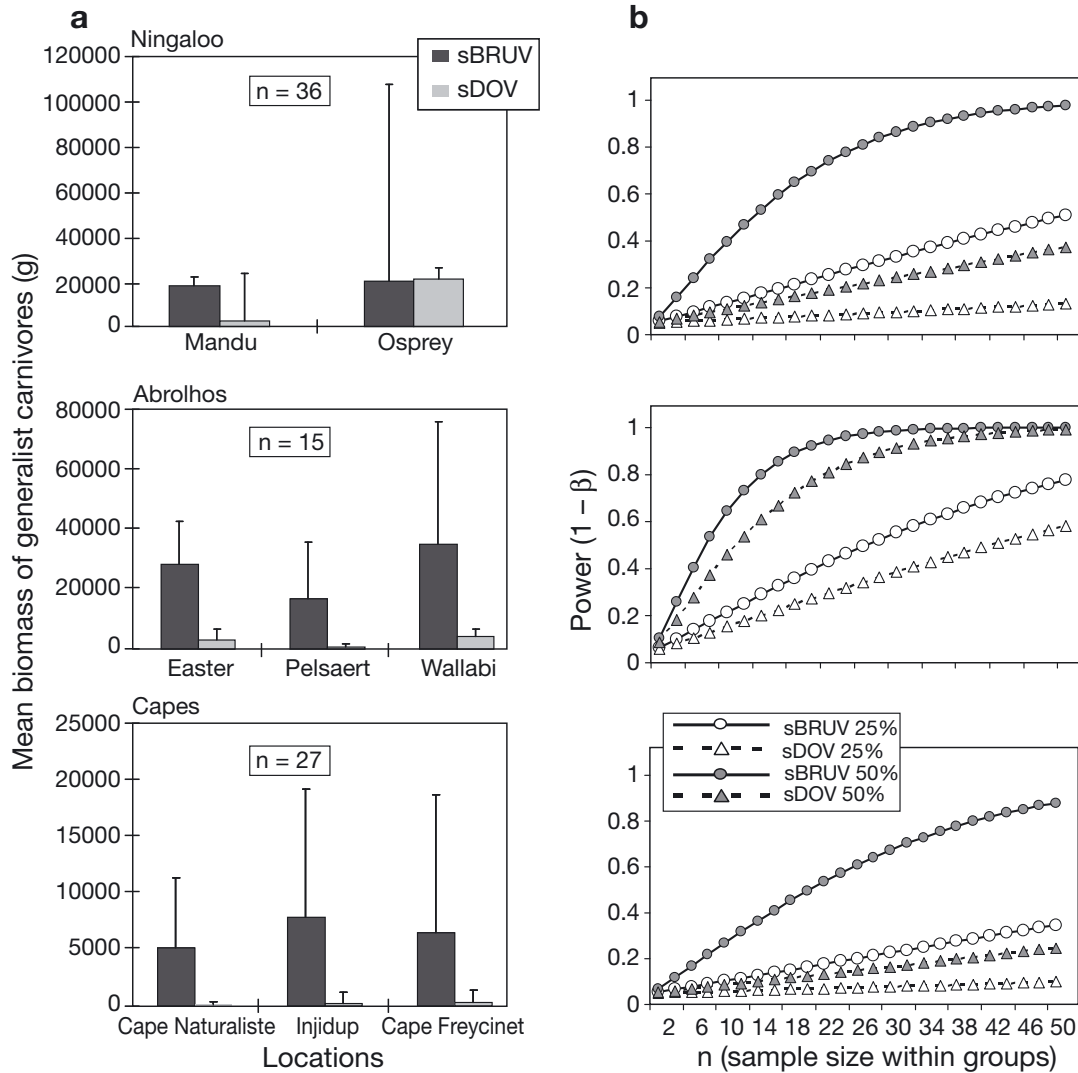


Fig. 4. Biomass of generalist carnivores. (a) Mean (+1 SD) biomass and (b) power to detect a change of 25 or 50% in the biomass of generalist carnivores at Ningaloo Reef, the Abrolhos Islands and the Capes region sampled by the stereo-BRUV (sBRUV) and stereo-DOV (sDOV) methods. See Fig. 2 for details on the units and standardisation between the regions

exception that there was no difference in the biomass of herbivores sampled by stereo-BRUV and stereo-DOV. In general, the present study has found that studies using stereo-BRUV are likely to find less variation in assemblage composition, greater mean values of variables such as species richness and biomass of generalist carnivores, greater power to detect change and be more time-efficient than studies using stereo-DOV.

The species richness of fish taxa observed in the stereo-BRUV samples was consistently higher than that seen in the stereo-DOV samples (Table 4). Species richness is known to be heavily influenced by sample unit area (Gray et al. 2004). The raw data presented in Table 4 have not been standardised between the methods; however, the sampling designs of each method

within each region were orthogonal and the only differences were the sample unit area of each methodology and the time of deployment. Moreover, the differences observed between each method within each region do not vary linearly with the increasing sample unit size of the stereo-DOV method. It is likely that the greater size of the stereo-DOV transects at the Abrolhos Islands would have resulted in greater estimates of variables such as species richness and biomass of generalist carnivores. However, any increase is likely to be highly non-linear and unlikely to result in any variation in the overall pattern of the results. The trend of increasing percentage of unique taxa sampled by stereo-BRUV from Ningaloo to the Capes suggests a trend of increasing relative efficiency of this method to sample the fish assemblage compared to stereo-DOV.

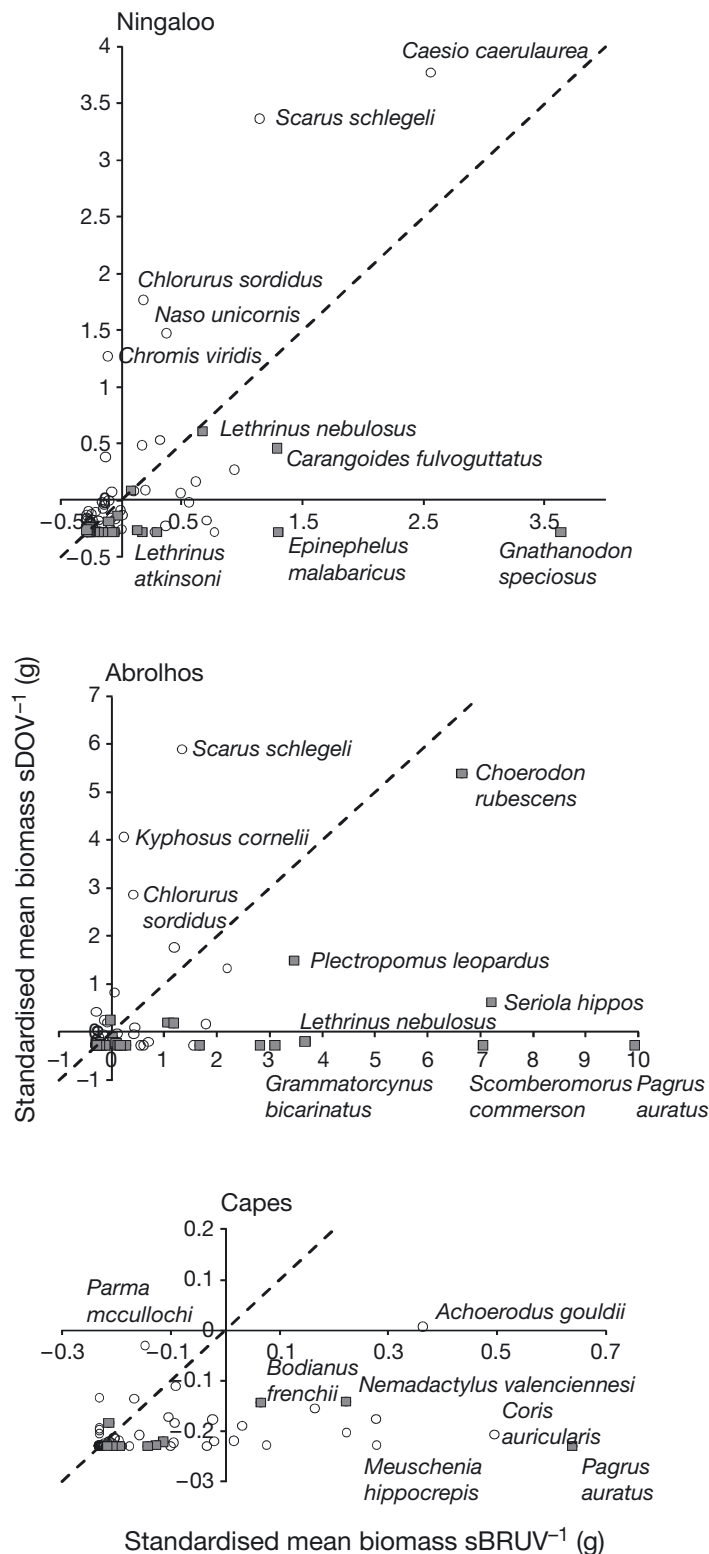


Fig. 5. Mean biomass of species sampled at Ningaloo Reef, the Abrolhos Islands and the Capes region by stereo-BRUV (sBRUV) and stereo-DOV (sDOV) methods, standardised between methods. (■) generalist carnivore species; (○) all other taxa. Dashed line indicates the relationship of equivalence between the 2 methods

This could be due to the stereo-BRUV methods sampling more effectively in the less abundant and less species-rich assemblage at the Capes, compared to Ningaloo where there is a greater species richness and overall abundance of the fish assemblage.

Further evidence of this is provided by the differences between the methods for sampling generalist carnivore and herbivorous species, which are apparent in the scatter plots comparing the standardised biomass estimated by each method (Fig. 5). Despite the lack of significant differences in the overall biomass of herbivores sampled by each method, it can be clearly seen that at Ningaloo and Abrolhos the stereo-DOV method sampled greater biomass of certain herbivorous species (*Scarus schlegeli*, *Chlorurus sordidus*). Conversely, the stereo-BRUV methods sampled greater biomass of many generalist carnivore species at Ningaloo and Abrolhos. However, the striking result at the Capes suggested that the stereo-DOV method sampled a much smaller proportion of the biomass of the majority of all reef fish, again suggesting that stereo-BRUV methods sample the less abundant and less species-rich assemblage more effectively.

There are some inherent difficulties in comparing these 2 different methodologies for sampling a given population, because each method has been purposely designed for slightly different situations. For example, stereo-BRUV methods are designed to sample generalist carnivore species at the point of deployment (Willis & Babcock 2000, Cappo et al. 2004, Harvey et al. 2007), whilst stereo-DOV surveys are designed to sample the fish that a diver would be able to observe whilst swimming a transect of a certain length and width. However, previous comparative studies have found that stereo-BRUV can also provide good information on herbivorous species (Watson et al. 2005). The results of the present study suggest that stereo-BRUV methods could provide a standardised method for obtaining representative samples of the assemblage of fishes for long-term studies across a range of locations. Cost-benefit optimization also indicated that stereo-BRUV methods are likely to require less staff time than stereo-DOV, which may result in stereo-BRUV surveys being more likely to collect the extensive time-series of data that will be useful for monitoring (Bernstein & Zalinski 1983). This largely reflects the ability to rapidly deploy up to 10 stereo-BRUV systems continuously, whereas the stereo-DOV surveys were limited to deploying 2 stereo-DOV dive teams at one time (Table 1).

Another important consideration relates to the spatial and temporal scales of the sampling. Stereo-BRUV samples, are obtained over several days (to reduce bait plume interference), only fish within 7 m of the camera are sampled during the 60 min deployment and the replicate samples are separated by at least 250 m (to

minimise bait plume interference). The distance of attraction of fish to the stereo-BRUV is also likely to be very variable between species with cryptic fish species only moving several cm, whilst large predatory fish travelling will travel 100s of m. Alternatively, stereo-DOV transects can cover 100 to 500 m² of habitat, take 1.5 to 6 min to sample, are separated by 10 to 15 m and are obtained during one dive. These differences in sampling procedure suggest that the spatial and temporal extent of sites sampled by the 2 methods will be very different. The longer deployment time of the stereo-BRUV is likely to average out the variability of the fish assemblage at the smaller scale of sampling and the larger sample unit area of stereo-DOV will capture more variability in the fish assemblage due to habitat heterogeneity. This interpretation is confirmed by the present study in that generally less variability was found in the assemblage of fish sampled using stereo-BRUV methods compared to stereo-DOV.

Future comparative studies should attempt to use the same sample unit area for the stereo-DOV method across regions and locations. The unequal transect size used in each region for the stereo-DOV method is an important limitation of the present study, but one that we feel does not compromise the overall pattern of differences between the methods between regions. In most studies that have used diver transects, the estimates of the fish assemblage are given with a unit measure dependent on the transect size (Limburg 1972, Roberts et al. 1992, Kulbicki 1998), and those from baited video stations are expressed as relative estimates with a unit measure dependent on the length of the deployment (Willis et al. 2003, Watson et al. 2007); this is because of the unknown influence of the bait plume on measures of the assemblage of fish (Harvey et al. 2007). However, it has been documented that samples of fish assemblages from diver-swum transects and baited video stations are both subject to the influence of fish behaviour (Kulbicki 1998, Watson et al. 2005, Cole et al. 2007). It would, therefore, be more accurate to express estimates from both methods as relative measures whilst using stereo-video techniques to provide an estimate of the sample unit area.

Acknowledgements. This study was conducted with logistical assistance from the Department of Fisheries, Western Australia. Financial assistance was received from The University of Western Australia (UWA), the West Australian and Australian Governments Natural Heritage Trust through the Northern Agricultural and South West Catchment Councils, and the Western Australian Marine Science Institute (WAMSI) Nodes 4.2 and 3.2. We thank R. Scott in the UWA workshop for construction of the stereo-video systems. We greatly appreciate the help given by Dr. B. Hutchins in identifying numerous fish species. This study forms part of a WAMSI Node 4.2 project to assist with the implementation of an ecosystem approach to the management of fisheries resources.

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Appendix 1. 4-factor ANOVAs examining species richness, biomass of generalist carnivores and biomass of herbivores sampled by the stereo-DOV and stereo-BRUV methods within each biogeographic region

Table A1. Ningaloo Reef. 4-factor ANOVA examining species richness, biomass of generalist carnivores and biomass of herbivores sampled by the stereo-DOV and stereo-BRUV methods within each location and site on the basis of data standardised between methods. Biomass of generalist carnivores and herbivores were transformed by $\ln(x + 1)$ before analysis. Sharks were excluded from the generalist carnivore group

Source	df	Species richness			Biomass of generalist carnivores			Biomass of herbivores			Denominator MS
		MS	F	p	MS	F	p	MS	F	p	
Method	1	0.29	1.07	0.49	0.55	3.68	0.31	0.08	0.49	0.61	Method × Location
Location	1	2.64	0.45	0.52	0.07	0.35	0.57	1.58	1.46	0.26	Site (Location)
Site (Location)	8	5.87	11.15	<0.01	0.19	1.31	0.25	1.08	4.91	<0.01	Residual
Method × Location	1	0.27	0.17	0.69	0.15	2.02	0.19	0.16	0.36	0.57	Method × Site (Location)
Method × Site (Location)	8	1.56	2.97	<0.05	0.07	0.51	0.84	0.45	2.02	0.06	Residual
Residual	80	0.53			0.14			0.22			
Total	99										

Table A2. Abrolhos Islands. 4-factor ANOVA examining species richness, biomass of generalist carnivores and biomass of herbivores sampled by the stereo-DOV and stereo-BRUV methods within each island group and site on the basis of data standardised between methods. Biomass of generalist carnivores and herbivores were transformed by $\ln(x + 1)$ before analysis. Sharks were excluded from the generalist carnivore group

Source	df	Species richness			Biomass of generalist carnivores			Biomass of herbivores			Denominator MS
		MS	F	p	MS	F	p	MS	F	p	
Method	1	462.4	10.88	<0.01	19.35	94.61	<0.001	1.62	3.85	0.1	Method × Site (Island group)
Island group	2	381.9	1.86	0.24	1.95	7.67	<0.05	0.21	0.33	0.73	Site (Island group)
Site (Island group)	6	205.83	6.28	<0.001	0.25	1.17	0.33	0.64	2.52	<0.05	Residual
Method × Island group	2	48.1	1.13	0.38	0.24	1.2	0.37	0.16	0.39	0.69	Method × Site (Island group)
Method × Site (Island group)	6	42.5	1.3	0.27	0.2	0.94	0.47	0.42	1.66	0.14	Residual
Residual	72	32.77			0.22			0.25			
Total	89										

Table A3. Capes region. 4-factor ANOVA examining species richness, biomass of generalist carnivores and biomass of herbivores sampled by the stereo-DOV and stereo-BRUV methods within each island group and site on the basis of data standardised between methods. Species richness was transformed by $\sqrt{x + 1}$ whilst biomass of generalist carnivores and herbivores were transformed by $\ln(x + 1)$ before analysis. Sharks were excluded from the generalist carnivore group

Source	df	Species richness			Biomass of generalist carnivores			Biomass of herbivores			Denominator MS
		MS	F	p	MS	F	p	MS	F	p	
Method	1	110.89	84.24	<0.01	9.34	97.16	<0.01	0.07	2.56	0.25	Method × Location
Location	2	1.6	4.18	0.07	0.08	0.36	0.71	0.03	0.4	0.69	Site (Location)
Site (Location)	6	0.38	1.86	0.09	0.21	1.35	0.24	0.06	1.05	0.4	Residual
Method × Location	2	1.32	4.87	0.06	0.1	0.29	0.76	0.03	0.26	0.78	Method × Site (Location)
Method × Site (Location)	6	0.27	1.31	0.26	0.33	2.11	0.06	0.11	1.81	0.1	Residual
Residual	144	0.21			0.16			0.06			
Total	161										