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Sample-size requirements for accurate length-frequency distributions of mesophotic reef fishes from baited remote underwater stereo video

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ABSTRACT

Accurate descriptions of size structure are important for adaptive management of marine fish populations subject to anthropogenic and environmental pressures. This requires monitoring programs that can measure the length of enough individuals within each focal fish population. This study assessed the number of length measurements required to accurately describe the size structure in a range of common mesophotic demersal fish species observed from baited remote underwater stereo video (stereo BRUV) sampling programs. Here, we use a resampling approach from an empirical length dataset collected as a part of ongoing monitoring efforts to characterize mesophotic reef fish assemblages across the continental shelf of eastern and southern Tasmania, Australia. The results suggest that, on average, between 60 and 120 individuals length measurements are needed from at least 20 to 2000 independent deployments to be 95% confident that samples reflected the “real” size structure of fishes captured using stereo BRUVs. It is important to note that the “real” size-structure of each fish species here is unknown but was parameterized by pooling all measurements across the stereo BRUV dataset. It should also be noted that the exact number of length measurements differs across species, with some less abundant species requiring substantial sampling effort. This study helps to inform initial sampling requirements for length measurements for monitoring programs using stereo BRUVs. It provides a methodology that can aid researchers to further refine the overall sampling effort for future fisheries and marine park monitoring applications.

1. Introduction

Size structure information provides important insights into the reproductive potential, growth and stability of demersal reef marine fish populations (Hixon et al., 2014; van Overzee and Rijnsdorp, 2015). A lack of smaller size classes of fish can suggest deficiencies in recruitment, while infrequency of larger size classes might indicate mortality of mature fish (Neumann and Allen, 2007). While there are multiple causes to alterations in size-class structure, fishing and climate change are recognized as some of the biggest contributors (Barnett et al., 2017; Queiros et al., 2018). Fishing causes size-selective removal of larger individuals that truncates the size structure of fish populations (Berkeley et al., 2004). Fishing can also influence the trophic structure of an ecosystem resulting in changes to size-selective predation (Mitchell et al., 2019) and through shifts in competitive interactions within and between species (Jenkins et al., 1999). Similarly, ocean warming has been suggested to cause widespread declines in organism body sizes through changes to water temperature, oxygen content and other ocean biogeochemical properties that directly affect ecophysiology of water-breathing organisms (Cresswell et al., 2019; Sheridan and Bickford, 2011). Ultimately, the age and size demographics of demersal reef populations are determined by the complex interactions among these factors because they typically experience multiple stressors simultaneously. Understanding these dynamics is critical to understanding the status of fishery or conservation actions (Cresswell et al., 2019) and how demersal reef fish populations are responding to environmental stressors (Audzijonyte et al., 2016). Therefore, accurately describing the size structure of demersal reef fish populations is important, but it requires capturing an adequate sample size of individuals to reliably characterize the length-frequency distribution of individual species components.

The sample size requirements for accurately describing the size structure of fishes has been undertaken for several small-bodied fish species (<250 mm maximum length) and evaluated using statistical resampling of simulated and empirical data sets (Schultz et al., 2016; Vokoun et al., 2001). For example, Vokoun et al., (2001) suggested sample sizes of 300 – 400 individuals were suitable to describe

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population size structure, and Miranda (2007) concluded that size structure can be adequately described with smaller sample sizes for fishes (150 – 425 individuals) with limited size structure distributions (i.e., maximum length 200 – 300 mm). However, specific assessments of sample size requirements for describing size structure for demersal mesophotic reef fishes are virtually absent in the published literature.

For demersal marine fish populations, there are numerous options to attain accurate size structure data. These methods can be classified as extractive and non-extractive. Extraction methods are associated with fishing gears such as seine nets, trawls, fishing lines and traps that capture fish enabling scientists to precisely measure them directly. While these methods are still commonly used in the fisheries sector, they are not ideal in situations where either the species or survey region are protected (Mallet and Pelletier, 2014; Przeslawski et al., 2018; Whitmarsh et al., 2017). Non-extractive methods often rely on underwater visual census and remotely deployed videography related methods to estimate the size of fish *in situ*. While each method has their associated bias, stereo-video systems, such as baited remote underwater stereo video (stereo BRUV), are increasingly being recognized (Langlois et al., 2020) for their ability to precisely measure the size of a broad range of fishes across multiple depths and habitat types (Collins et al., 2017; Heyns-Veale et al., 2016; Wellington et al., 2018) as well as the provision of a permanent record that can be reviewed to reduce interobserver variability (Cappo et al., 2009). However, the often limited and fixed field of view can limit the number of length measurements taken within the footage. These length measurements are commonly taken at MaxN (i.e. the maximum number of individuals for that species present in a single frame within a deployment; Langlois et al., 2020). There is a requirement that the individual fish needs to be clearly visible in the field of view of both cameras. However, it is often hard to follow individuals, particularly if in a school, and identify accurately to avoid issues of re-measuring the same fish, and some individuals may be obscured by others, the substrate, bait bag or diode arm. In some situations, as few as 30% of individuals can be measured (Mitchell et al., accepted). The reduced number of individual fish being measured impacts the accuracy of the length structure data from stereo BRUVs.

Stereo BRUVs are now accepted as a standard operating protocol for monitoring demersal reef fishes on mesophotic reefs throughout Australia, particularly in the network of recently established Australian Marine Parks (Przeslawski et al., 2019) and increasingly world-wide (Langlois et al., 2020). Accordingly, the aims of this study were two-fold: 1) to assess the number of length measurements required from stereo BRUVs to accurately describe the size structure of typical demersal fish populations and the key species they are composed from and, 2) calculate how many individual stereo BRUV deployments would typically be required in a survey program to reach this number of length measurements. The datasets utilized were from a range of sampling programs undertaken on temperate mesophotic rocky reef systems in shelf waters of eastern and southern Tasmania, Australia, and were examined via statistical resampling procedures. By focusing the analyses on a suite of fisheries important fish species that are often applied as indicators for quantifying population structure change (e.g., Hill et al., 2018), we provide further refinement around optimal sample sizes required in monitoring programs designed for both conservation and fisheries management within this region.

2. Materials and methods

2.1. Study region

This study used stereo BRUV deployments collected from six locations, including; Tasman Fracture Marine Park, South and South-east Cape, the Friars, Butlers Point and Flinders Marine Park. Combined, these locations provide coverage representing ~500 km of coastline from the south-west to north-east of Tasmania (Fig. 1). Locations covered a range of depths from ~30 to 180 m and consisted of predominantly sessile invertebrate dominated reef habitats. The southern locations fall in and around the sanctuary zone (IUCN II) of the Tasman Fracture Marine Park which has been in place since 2007. This region is known for its' unique sessile invertebrate communities which appear to be associated with the exposure to regular south ocean fronts and the Zeehan Current (Monk et al., 2016). The Friars and Butlers Point

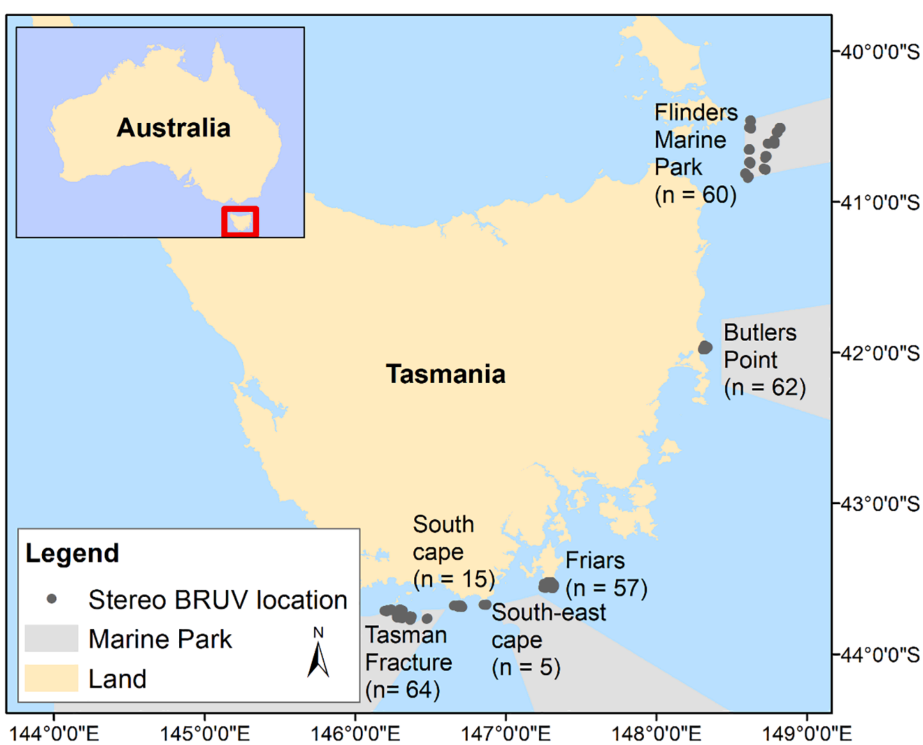

Fig. 1. Location of stereo BRUV deployments used in resampling procedures for assessing sample size requirements for size class structure.

represent locations that remain open to commercial and recreational fishing pressures, while the northern locations fall within the multiple-use zone (IUCN IV) of the Flinders Marine Park which received low to moderate commercial fishing effort (~2000 kg/year) on the continental shelf before its declaration in 2007. Within the Flinders Marine Park, demersal trawling was concentrated on the outer shelf, while hook, line and gillnet fishing were more dispersed across the shelf (Pitcher et al., 2016). Since 2007, demersal trawling has been prohibited, but some hook and line and recreational fishing is allowed on the shelf of the Marine Park (Williams et al., 2013).

2.2. Sampling design

A total of 251 stereo BRUV deployments were collected during the austral summer/autumn months between 2012 and 2015 (Fig. 1). The exact sampling designs for each location are detailed in Monk et al. (2016), Lyle et al. (2017) and Hill et al. (2018). Each stereo BRUV deployment represents a 60 min soak time following the standard operating procedure described in Langlois et al. (2018). Stereo camera pairs had 700 mm separation with a camera incidence angle of 8° mounted to a galvanized steel frame allowing a 500 mm height clearance above benthos. Bait arm length was 1.5 m in front of the cameras and the wire mesh bait holders contained ~1 kg of crushed pilchards (*Sardinops neopilchardus*). Deployments in depths > 50 m were artificially illuminated using seven Royal Blue CREE XLamps XP-E LEDs (delivering a radiant flux of 350–425 mW at wavelength ranging from 450 to 465 nm). Blue lights were used as they avoid potential behavioural biases (Fitzpatrick et al., 2013). The stereo BRUVs were deployed during daylight hours avoiding 1 h after sunrise and before sunset. Concurrent deployments were separated by a minimum of 250 m to avoid potential confounding following Langlois et al. (2018).

2.3. Video annotation and length measurements

All individual fishes were identified to their lowest taxonomic level, with their relative abundance estimated using the maximum number of fish occurring in any one frame for each species (MaxN; Ellis and Demartini, 1995). Only fish within a standardized 4 m field of view of the bait bag were annotated and measured. The length of all fish species was recorded for as many individuals as possible occurring within frames adjacent to MaxN as some individuals were obscured by other fish. Calibrations, annotations and measurements were performed using methods outlined in Langlois et al. (2020) with calibrations completed in software Cal (www.seagis.com.au), and annotations and

Table 1
Distribution, ecology and fisheries information for focal species.

Family	Scientific name	Distribution and ecology				Fisheries	
		Australian distribution	Habitat	Depth range	Trophic ecology	Fishery	Target/ Incidental
Cheilodactylidae	*Nemadactylus macropterus*	Southern Australia (Perth to Coffs Harbour)	Soft sediment	0–400 m	Benthic invertivore	Commercial/ Recreational	Target
	Chirodactylus spectabilis	South-eastern Australia (Victor Harbour to Sydney)	Hard bottom	0–50 m	Benthic invertivore	Commercial/ Recreational	Target
	Nemadactylus douglasii	South-eastern Australia (Melbourne to Brisbane)	Hard bottom	0–200 m	Benthic invertivore	Commercial/ Recreational	Target
Cyttidae	*Cyttus australis*	South-eastern Australia (Ceduna to Coffs Harbour)	Benthopelagic/Soft sediment	20–250 m	Benthic invertivore	Commercial/ Recreational	Target
Dinolestidae	*Dinolestes lewini*	Southern Australia (Perth to Sydney)	Benthopelagic	0–70 m	Higher carnivore	Commercial/ Recreational	Target
	Notolabrus tetricus	South-eastern Australia (Adelaide to Sydney)	Mixed bottom	0–60 m	Benthic invertivore	Commercial/ Recreational	Target/ Incidental
Latridae	*Latris lineata*	Southern Australia (Albany to Sydney)	Hard bottom	0–400 m	Benthic invertivore	Commercial/ Recreational	Target
Monacanthidae	*Meuschenia scaber*	Southern Australia (Margaret River to Port Macquarie)	Hard bottom	0–200 m	Benthic invertivore	Bycatch	Incidental
	Thamnaconus degeni	Southern Australia (Esperance to Bairnsdale)	Mixed bottom	5–80 m	Benthic invertivore	Commercial/ Recreational	Target/ Incidental
	Meuschenia australis	South-eastern Australia (Victor Harbour to Bairnsdale)	Hard bottom	0–30 m	Browsing herbivore	Commercial/ Recreational	Target/ Incidental
	Meuschenia freycineti	Southern Australia (Perth to Coffs Harbour)	Mixed bottom	0–50 m	Browsing herbivore	Commercial/ Recreational	Target/ Incidental
	Acanthaluteres vittiger	Southern Australia (Perth to Flinders Island)	Mixed bottom	0–40 m	Browsing herbivore	Commercial/ Recreational	Target/ Incidental
	Eubalichthys gunnii	South-eastern Australia (Adelaide to Flinders Island)	Hard bottom	5–50 m	Browsing herbivore	Commercial/ Recreational	Target/ Incidental
Mordiae	Morid cods	South-eastern Australia (Adelaide to Coffs Harbour)	Mixed bottom	10–350 m	Higher carnivore	Commercial/ Recreational	Target/ Incidental
Mullidae	*Upeneichthys vlamingii*	Southern Australia (Geraldton to Sydney)	Soft sediment	0–200 m	Benthic invertivore	Commercial/ Recreational	Target
Neosebastidae	*Neosebastes scorpaenoides*	South-eastern Australia (Esperance to Sydney)	Hard bottom	0–200 m	Benthic invertivore	Recreational	Target/ Incidental
Platycephalidae	*Platycephalus bassensis*	Southern Australia (Perth to Coffs Harbour)	Soft sediment	0–100 m	Higher carnivore	Commercial/ Recreational	Target
	Platycephalus richardsoni	South-eastern Australia (Victor Harbour to Coffs Harbour)	Soft sediment	20–450 m	Higher carnivore	Commercial/ Recreational	Target
Scyliorhinidae	*Cephaloscyllium laticeps*	Southern Australia (Esperance to Bairnsdale)	Mixed bottom	0–80 m	Higher carnivore	Bycatch	Incidental
Sebastidae	*Helicolenus percoides*	South-eastern Australia (Portland to Coffs Harbour)	Mixed bottom	10–400 m	Higher carnivore	Commercial/ Recreational	Target/ Incidental
Squalidae	*Squalus spp*	Australia wide (Port headland to Townsville)	Soft sediment	0–600 m	Higher carnivore	Commercial	Target/ Incidental
Triakidae	*Mustelus antarcticus*	Southern Australia (Perth to Sydney)	Soft sediment	0–350 m	Higher carnivore	Commercial	Target/ Incidental

measurements were done in the software EventMeasure Stereo (www.seagis.com.au).

2.4. Selection of potential focal species

From the 94 potential species, 22 demersal fish species were chosen based on their numerical abundance and their relevance to the fishing sector (Tables 1 and S1). Many of these species have large distributions spanning temperate Australia and cover a wide range of maximum lengths (i.e., 200–2000 mm). Some are targeted by both commercial and recreational fishers using various fishing gears, some of which are prohibited in multiple-use zone of the Flinders Marine Park (Table 1).

2.5. Statistical analysis

2.5.1. Number of length measurements

A resampling approach developed by Schultz et al. (2016) was adapted to evaluate the number of length measurements required to obtain a representative size-structure distribution for each of the focal fish species from the stereo BRUVs. This approach involved a random subsample, with replacement, of a range of individual lengths from the entire pooled stereo BRUV dataset. For this study subsample sizes ranged from 5 to 500 individual fish, at 5-fish intervals (i.e., 5, 15, 20… 500) with minimum and maximum lengths parameterized as smallest and largest fish measured for that species. The subsample sizes represent the approximate lower and upper limit of the number of fish encountered in a school that could be captured in a stereo BRUV field of view with moderate sampling effort.

To evaluate the accuracy of characterizing a size-structure distribution using different subsample sizes, the size frequencies of each subsample was compared to the original pooled sample to estimate mean absolute difference (MAD) in relative frequency in each length interval using the following equation:

$$\widehat{\mathrm{MAD}} = \frac{1}{r}\sum_{i=1}^{r}\left(\frac{1}{b}\sum_{j=1}^{b}\left|p(y_j) - p\left(\widehat{y}_{ij}\right)\right|\right) \quad (1)$$

where $p(y_j)$ was the proportion of individuals in the jth interval from the original pooled sample, $p(\widehat{y}_{ij})$ was the proportion of individuals in the jth interval and the ith subsample, b was the number of length intervals, and r the number of iterations. Additional resampling was used to examine the effect of size interval on MAD estimates. The width of individual size class interval can change the interpretation of size-class distributions (e.g., Langlois et al., 2012; Vokoun et al., 2001). For each subsample size, 1000 iterations were generated to calculate estimated MAD and compute 95th percentile for each of three size class intervals of 10, 20, and 50 mm. These size class intervals represent commonly used size class bins for marine fishes. For eample, Anderson and Neumann (1996) suggests 10 mm intervals for fish that reach 300 mm, 20 mm intervals for fish that reach 600 mm, and 50 mm intervals for fish that reach 1500 mm maximum length. The estimated MAD and the upper 95th percentile of resamples for each subsample size were plotted. The interpretation of these plots is straight forward, providing the relative accuracy of a given sample size. For example, the sample size at which the 95th percentile declines to below a MAD of 5% is interpreted as the number of length measurements needed to yield sample size-class distribution across all length bins within 5% of the size-class distribution of the original pooled dataset 95% of the time. It is important to note that the true size-structure of the fish population is unknown. However, Langlois et al. (2012) has shown that size structure information captured at MaxN from stereo BRUVs is similar to other sampling methods such as line and trap data.

2.5.2. Number of stereo BRUV deployments

The proportion of fish measurable at MaxN and the 95th percentile MAD values were used to calculate the number of stereo BRUV deployments required to reach the minimum length measurement sample size to adequately describe species/population size structure. This was calculated using the following equation:

$$n = \frac{MAD95th}{p(y) \times \overline{x}(m)} \quad (2)$$

where, for each species, n is the estimated number of stereo BRUV samples, *MAD95th* is the 95th percentile MAD value, $p(y)$ was the proportion of individuals measurable, and $\overline{x}(m)$ was the mean MaxN calculated across all 251 stereo BRUV samples.

3. Results

Ninety-four species were recorded across the surveyed population (S1), with 22 retained for analysis due to their relevance to fisheries. *Meuschenia scaber*, *Nemadactylus macropterus* and *Thamnaconus degeni* were the most abundant with mean MaxN per stereo BRUV drop of 5.4, 4.5 and 3.1, respectively (Table 2). *Helicolenus percoides* was the next most abundant with a mean MaxN of 1.9, followed by *Dinolestes lewini* (1.5), Morid cods (1.1) and *Notolabrus tetricus* (0.9; Table 2). *Latris lineata, Cephaloscyllium laticeps* and *Cyttus australis* were moderately abundant with between mean MaxN of between 0.5 and 0.6 (Table 2). *Meuschenia australis*, *Meuschenia freycineti*, *Acanthaluteres vittiger*, *Neosebastes scorpaenoides, Eubalichthys gunnii*, *Upeneichthys vlamingii, Chirodactylus spectabilis*, *Mustelus antarcticus*, *Nemadactylus douglasii*, *Platycephalus bassensis*, *Platycephalus richardsoni* and *Squalus* spp were the least abundant with a mean MaxN of $<$ 0.5 per drop (Table 2).

Like the proportion of length measurements achieved at MaxN, the range in species length and the proportion measured varied considerably between species, ranging from 31 mm *Cyttus australis* to 1707 mm for a *Mustelus antarcticus* (Tables 2; S1). *Platycephalus bassensis*, *Squalus* spp, *Notolabrus tetricus, Platycephalus richardsoni* and *Mustelus antarcticus* were the most measurable species with $>$ 80% of individuals at MaxN being able to be measured (Table 2). *Cyttus australis, Dinolestes lewini, Thamnaconus degeni, Eubalichthys gunnii* and *Chirodactylus spectabilis* were the least measurable species with $<$ 50% of individuals being measured. Complete summaries of proportions measured, and lengths are provided in Tables 2 and S1, respectively.

As a first step to examining length-frequency distributions in individual species, the influence of using differing interval widths to represent size class distributions was examined. However, when visually comparing the length-frequency plots for the 10-, 30- and 50-mm size class intervals, similar size structure distributions were observed for most of the 22 fish species examined (Fig. 2). For example, all three size class intervals for the length-frequency plot for commercially and recreational prized *Latris lineata* suggests a peak in individuals around 470 mm (Fig. 2). Despite similar size structure distributions between size class intervals, larger intervals exhibited greater MAD values for a given length measurement sample size for most species (Fig. 3). However, regardless of size class interval, a consistent asymptotic decrease in MAD estimates was observed for all species (Fig. 3). While the fish species exhibited different MAD values across the three size class bins, the largest decreases in MAD, thus increase in accuracy, occurred within the first 50 individuals sampled, with most species reaching an acceptable reduction in MAD (to 5%) with less than 100 individual length measurements (Fig. 3, Table 2). For all species, the length measurement sample size required for the upper 95th percentile of the error to be below 5% MAD, increased with the size class interval used, with a minimum number of length measurements of 30 to 105 individuals required for the 10-mm size class bins, 55–130 individuals for 30-mm size class bins, and 80–135 individuals for 50-mm size class bins (Fig. 3).

Using the minimum number of individuals required to be measured to achieve a reliable MAD (below 5% and within the 95% percentile), and accounting for the average proportion of individuals able to be

Table 2
Mean abundance (MaxN), proportion measured, 95th percentile mean absolute difference (MAD 95th) values and estimated number of deployments required for the focal species based on the pooled 251 stereo BRUV dataset. A complete list of species including summed abundance (MaxN) and length summaries are provided in S1 Table.

Family	Scientific	Mean MaxN per drop	Proportion measured at MaxN	No of fish required for reliable estimate (MAD 95th)			Estimated no of deployments for accurate length-frequency data		
				10 mm bin	30 mm bin	50 mm bin	10 mm bin	30 mm bin	50 mm bin
Cheilodactylidae	*Nemadactylus macropterus*	3.07	0.65	40	90	100	20	45	51
	Chirodactylus spectabilis	0.17	0.48	55	105	115	690	1318	1443
	Nemadactylus douglasii	0.10	0.68	50	100	115	738	1476	1698
Cyttidae	*Cyttus australis*	0.52	0.24	65	110	120	526	891	972
Dinolestidae	*Dinolestes lewini*	1.48	0.26	65	115	115	166	295	295
	Notolabrus tetricus	0.94	0.92	60	115	135	69	133	156
Latridae	*Latris lineata*	0.75	0.63	45	95	110	94	199	230
Monacanthidae	*Meuschenia scaber*	5.43	0.52	60	105	110	21	37	39
	Thamnaconus degeni	4.48	0.40	55	100	100	31	56	56
	Meuschenia australis	0.49	0.65	75	120	135	238	381	429
	Meuschenia freycineti	0.40	0.60	55	110	120	226	453	494
	Acanthaluteres vittiger	0.36	0.62	95	130	110	426	583	493
	Eubalichthys gunnii	0.27	0.46	85	125	135	688	1012	1093
Mordiae	Morid cods	1.09	0.64	45	100	125	65	144	180
Mullidae	*Upeneichthys vlamingii*	0.21	0.58	90	125	120	729	1012	972
Neosebastidae	*Neosebastes scorpaenoides*	0.28	0.77	105	120	100	479	548	456
Platycephalidae	*Platycephalus bassensis*	0.09	0.96	85	120	125	970	1369	1426
	Platycephalus richardsoni	0.07	0.89	80	120	135	1255	1883	2118
Scyliorhinidae	*Cephaloscyllium laticeps*	0.58	0.57	35	75	105	107	230	321
Sebastidae	*Helicolenus percoides*	1.86	0.50	60	115	125	65	124	135
Squalidae	*Squalus* spp	0.07	0.94	100	125	130	1569	1961	2039
Triakidae	*Mustelus antarcticus*	0.10	0.80	30	55	80	377	690	1004

reliably measured per stereo BRUV drop, we estimate that across our 22 focal species, the minimum number of stereo BRUV deployment per species ranged between 20 for *Nemadactylus macropterus* to 1569 for *Squalus* spp. based on 10-mm length-frequency bins (Table 2). Slightly more stereo-BRUV deployments were estimated to be required for larger size class intervals, ranging from 37 to 1961 and 39 to 2118 for the 30- and 50-mm size class bins, respectively (Table 2).

4. Discussion

This study found the minimum number of individual length measurements required to accurately describe the size-class structure of mesophotic reef fishes from stereo BRUVs varied greatly between species, ranging from 30 to 135 individuals. The results also suggested that, while the size class interval used to generate length-frequency distributions did not appear to overly influence the overall pattern, slightly more individual length measurements are required to adequately describe the size class distribution when using larger intervals. From these analyses, it is recommended that, generally, stereo BRUV monitoring programs should aim to collect measurements from at least 60, 110, or 120 individuals for length-frequency analyses when using 10-, 30-, and 50-mm size class intervals, respectively, to be 95% confident that samples reflected the "real" size class distribution of the species of interest. This should be, on average, achievable from 430, 680 and 730 stereo-BRUV deployments for length-frequency analyses using 10-, 30-, and 50-mm size class intervals, respectively. Though, it should be noted that the exact number of individual measurements changes between species, with species that exhibit higher encounter probabilities (such as *Notolabrus tetricus* and *Nemadactylus macropterus*) generally required fewer number of stereo BRUV deployments.

The number of individual length measurements found in our study agrees with previous research. Anderson and Neumann (1996) recommended that at least 100 individual fish should be measured to describe a length-frequency distribution to meet fisheries management objectives. Similarly, Gilliland (1987) compared the various length measurement requirements to examine the size class structure of the freshwater fish, *Micropterus salmoides*, sampled using electrofishing and concluded that 150 individual measurements were adequate. More recent work of Kritzer et al. (2001), Vokoun et al. (2001), Miranda (2007) and Schultz et al. (2016) suggest that between 100 and 1200 individual measurements are required to accurately capture the size-class structure of a range of different (predominately) freshwater fish species. However, none of these studies explored how many sample replicates (i.e., stereo BRUV deployments) would be required to attain these individual measurements.

For most species, it would take a high sampling effort of ≫200 stereo BRUV deployments to attain an adequate number of length measurements. In most monitoring programs having to deploy this number of stereo BRUVs would be an unreasonable expectation due to economic and logistical costs. It should be noted that our analysis did not account for heterogeneous encounter probabilities that are common for many fishes due to habitat/depth affinities (Katsanevakis et al., 2012), sampling gear (Langlois et al., 2012; Monk et al., 2012) and size/age classes utilizing different habitats or protection zones (Ortiz and Tissot, 2008). In many cases, the absence of an individual, or a particular size, from a dataset may be reflective of imperfect detection due to sampling bias rather than true absence (Monk, 2014). Realistically, the number of length measurements and deployments suggested in this study are likely to be an overestimate and are only applicable to fish populations associated with mesophotic temperate reef habitats. More refined estimates could be achieved by accounting for these heterogeneous encounter rates associated with habitat, and perhaps researchers may be able to increase the number of length measurements obtained without the need to increase (even a decrease in) the number of stereo BRUV deployments suggested here.

It is also important to note that the accuracy of the length-frequency distribution used to estimate the number of length measurements cannot be resolved by the analysis used here. We acknowledge that stereo BRUVs have been criticized for potential biases associated with limiting measurements to individuals at MaxN, which may reduce the "tails" in

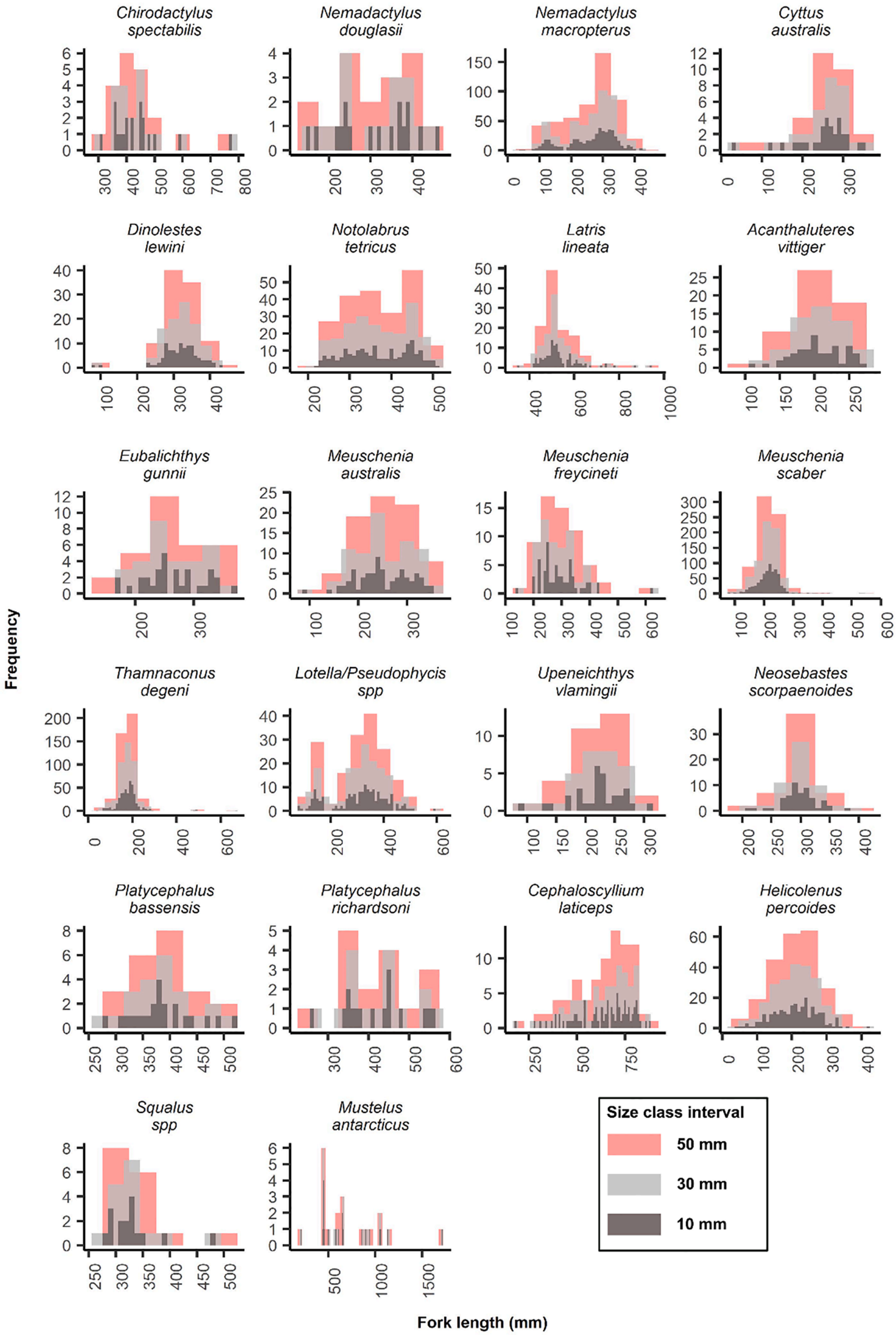

Fig. 2. Length-frequency distributions showing the effects of different size class intervals.

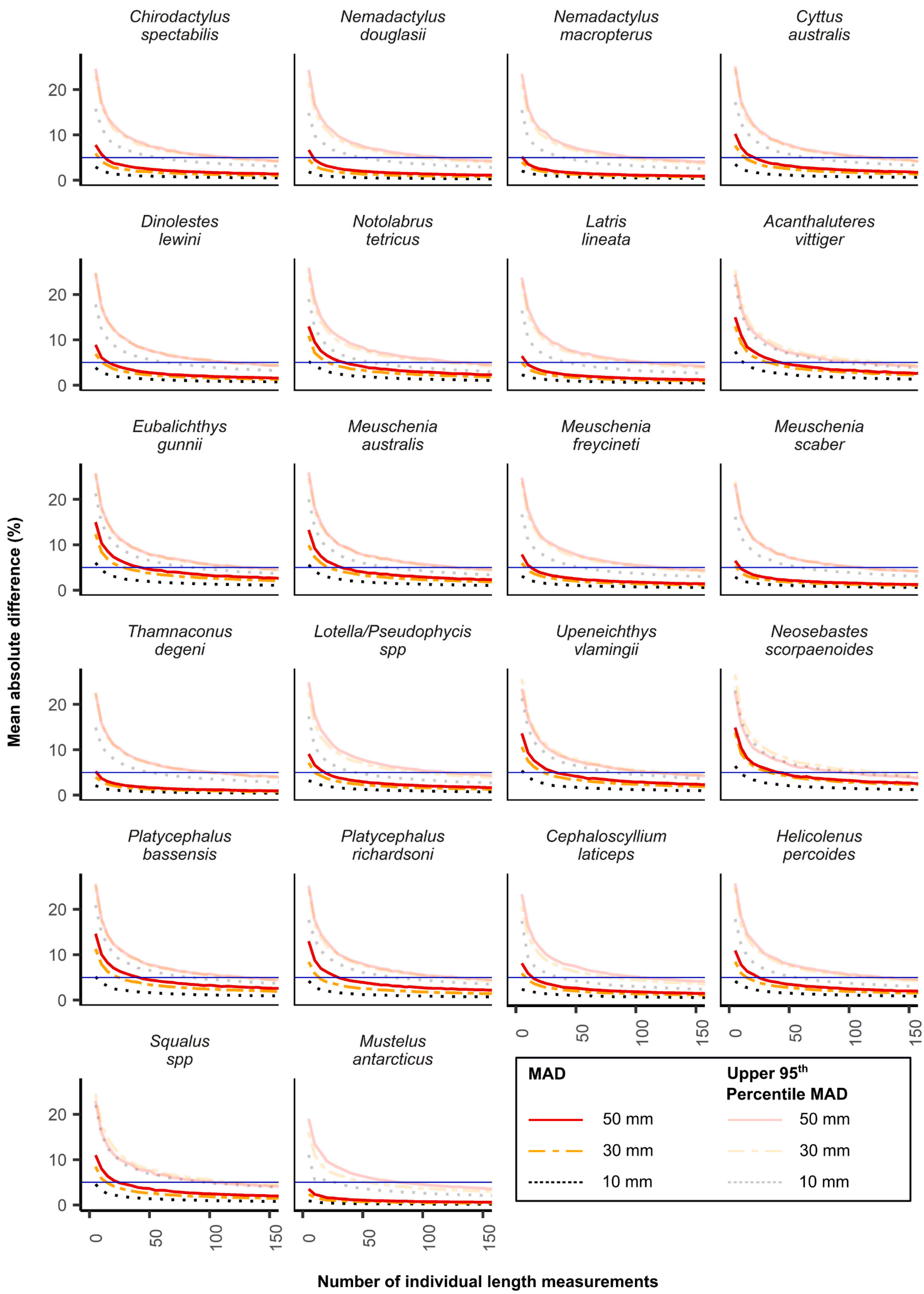

Fig. 3. Mean absolute difference (MAD) in relative size class bins (darker shading lines) and upper 95th percentiles (lighter shaded lines) between subsamples and original pooled stereo BRUV samples for various subsample sizes for each species. Line format represents different size class intervals (red solid line, 50 mm; orange dash line, 30 mm; black dotted line, 10 mm). The blue line indicates the 5% MAD threshold. Also, note that only the first 150 of the possible 500 measurements are shown for clarity as all species reached 5% MAD by this value. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the real length-frequency distribution (Harvey et al., 2013; Langlois et al., 2012). However, we argue that all fish sampling methods are size-selective and provide a biased representation of the real length distribution. We also did not account for situations when sampling habitats that do not attract all lengths equally (such as monitoring a species with known ontogenetic habitat preferences). As such we do caution readers that our results relate to temperate water mesophotic fishes captured using stereo BRUVs. However, the approach used here provides a template that could be used to further refine monitoring programs focusing on different species in other marine regions and habitats.

While researchers may have differing levels of acceptable accuracy, our results do highlight that a substantial number of deployments may be needed in situations when a high degree of accuracy is required (such as fisheries stock assessments). In such circumstances where a high level of accuracy is required, it is important to consider the ramifications of under-sampling length-frequency distribution. Previous research, such as Harvey et al. (2002), have illustrated scenarios in which imprecise fish lengths produce inaccurate biomass estimates and may provide an insight into the potential effects of under-sampling length-frequency distributions. As stereo BRUVs continue to be used for length/biomass related metrics in monitoring programs, it is important to get a better understanding of these potential effects. While previous studies have focused on understanding the effort required to accurately sample abundance or lumped size categories (such as the number of legal-sized fish) from stereo BRUVs (e.g., Hill et al., 2018; Langlois et al., 2012), our study helps to inform initial sampling requirements for length measurements for monitoring programs using stereo BRUVs. However, more research is required to understand the sampling effort required to accurately capture length-frequency data from stereo BRUVs across a broader range of habitats and species. The approach used here provides a means to further refine length/biomass related monitoring programs and helps to initially inform sample size requirements for length measurements for monitoring using stereo BRUVs for fisheries and marine park monitoring applications, which are increasingly using size-based indicators as descriptors associated with fishing pressure in both temperate (e.g., Stuart-Smith et al., 2017) and coral reef habitats (e.g., Robinson et al., 2017).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.107262.

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