Estimation of reef fish length by divers and by stereo-video: a first comparison of the accuracy and precision in the field on living fish under operational conditions.

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ABSTRACT

Using simultaneous measurements from an underwater stereo-video system the accuracy and precision of length estimates of reef fish made by three experienced diver scientists under field conditions is determined. The trial showed that under optimal conditions the divers' estimates were very accurate (mean error = 0.87 cm) but lacked precision (mean std dev = 5.29 cm). The effects of the low precision are then demonstrated by using these field estimates to model the theoretical statistical power of the scientific divers to detect changes in the mean length of three species of fish from New Zealand coastal waters. The results suggest that the experienced diver scientists would have a much lower statistical power than stereo-video measurements to detect changes in the mean length, especially where low numbers of fish are recorded or where a research program aims to detect a change in the mean length of a fish population of 30% or less.

KEYWORDS: Fish visual census, Fish length Estimates; Reef fish; SCUBA divers; Stereo-video; Statistical power

INTRODUCTION

Visual counts by SCUBA divers are the predominant technique for enumerating the abundance and composition of reef fish assemblages on temperate and coral reefs (e.g., Mapstone and Fowler, 1988; Holbrook et al., 1994; Francour, 1997; Kingsford, 1998). There are a number of methodological errors and biases associated with visual census techniques, most of which result in the underestimation of population densities (Jones and Chase, 1975; Andrew and Mapstone, 1987; Greene and Alevizon, 1989; Thompson and Mapstone, 1997; Kingsford, 1998). More recently researchers have tried to identify potential sources of bias and methodological error, and have attempted to quantify their magnitude or effect. Sources of bias and error that have been identified and investigated include:

- the method of counting (Sale and Douglas, 1981; DeMartini and Roberts, 1982; Kimmel, 1985; Bortone et al., 1986; Sanderson and Solonsky, 1986; Thresher and Gunn, 1986; Greene and Alevizon, 1989; Bortone et al., 1991; Samoilys, unpublished 1992; Mapstone and Ayling, unpublished 1993);

- the number of species of fish that can be effectively counted simultaneously (Russell et al., 1978; Greene and Alevizon, 1989; Lincoln- Smith, 1989);

- the swimming speed with which counts are undertaken (Mapstone and Fowler, 1988, Lincoln-Smith, 1988; St. John et al., 1990);

- the shape and size of sampling units (Sale and Sharp, 1983; Fowler, 1987; McCormick and Choat, 1987; Mapstone and Fowler, 1988; Buckley and Hueckel, 1989; Mapstone and Ayling, unpublished 1993);

- the behaviour of fish towards a SCUBA diver (Chapman et al., 1974; Chapman, 1976; Chapman and Atkinson, 1986; Cole, 1994; Kulbicki, 1998; Francour et al., 1999);

- the non-random movement of fish (Watson et al., 1995);

- the effect of inter-observer variability (Darwall and Dulvy, 1996; Thompson and Mapstone, 1997);

- errors in length estimation of reef fish (Bell et al., 1985; St. John et al., 1990; Darwall and Dulvy, 1996; Harvey et al., 2001 a, b).

In this paper this last issue, the magnitude and effects of error in estimates of reef fish length is addressed.

Error associated with visual estimates of reef fish length

Bell et al. (1985) and Darwall and Dulvy (1996) investigated the magnitude of errors in length estimates of reef fish by using model silhouettes of fish to train SCUBA divers and determine the extent of their error. Their results and conclusions imply that the errors in length estimates made by the SCUBA divers in their trials were not large enough to cause concern. Harvey et al. (2001a) demonstrate that length estimates of fish silhouettes made by experienced and novice research divers were both less accurate and less precise than those made with an underwater stereo-video. The results obtained by the experienced research divers used in their study were similar to those recorded by Bell et al. (1985). These length estimates were then used to predict the statistical power of experienced and novice scientific divers and a stereo-video to detect changes in the mean length of three common species of coastal reef fish from around New Zealand (Harvey et al. 2001 b). This demonstrated that for an equivalent number of samples, length estimates from a stereo-video provided greater statistical power to detect changes in the mean length of reef fish than length estimates from SCUBA divers.

The conclusions of Bell et al. (1985), Darwall and Dulvy (1996) and Harvey et al. (2001 a, b) were all based on length estimates of rigid and non-mobile model silhouettes of fish. It is logical to expect that the accuracy and precision of a SCUBA diver’s length estimates for a real fish might be different to those for a static silhouette. It might be expected that under field conditions, the accuracy and precision of a diver’s length estimates could deteriorate due to the rapid movement of target species, the necessity to assess the lengths of many fish of different species over a short period of time and a range of distances. Furthermore, variability in water visibility between sites and times, and the physiological effects of being immersed in salt water (Baddeley, 1965; Baddeley et al., 1968; Hollien and Rothman, 1975) will also have an impact on the accuracy and precision of diver estimates. Conversely, it might be thought that diver estimates will be better in the field, as they have other objects in their field of view that can provide a comparative scale. For example, from prior experience a diver may know the diameter of a holdfast of a particular species of kelp, or the approximate length at which a species of protogynous labrid changes sex and use this knowledge to assist in the length estimation of a fish in close proximity.

The accuracy and precision of length estimates of reef fish in the field have not been quantitatively investigated. Some researchers have attempted to validate the accuracy of their field length estimates by either spearing or netting individual fish to compare their estimates with the real length, but have only taken small numbers of samples (e.g. Bellwood and Alcala, 1988). Other researchers quote the results of experiments by Bell et al. (1985), or other studies (eg. Polunin and Roberts, 1993) to justify the assumption that their length estimates are both accurate and precise, without quantitatively testing this assumption. In the field, it is difficult for SCUBA divers to determine the accuracy and precision of their length estimates of real fish due to not knowing the true length.

This study uses measurements from a stereo-video system as an accurate indication of true length, against which to compare diver estimates. The rationale of using a stereo-video as a field control is based on the assumption that measurements for live fish are as accurate and precise as those made of static objects under ideal recording conditions. Data from a subset of stereo-video measurements described in Harvey and Shortis (1998) show that in the field (between distances of 3 and 8 m) this system had a mean error of -0.23 cm (SE = 0.11 cm), a mean relative error (RE) of -0.34% (SE = 0.16%) and a coefficient of variation (CV) of 0.56%. This subset of measurements was made horizontally between fixed points 68.75 cm apart with only one measurement made per image rather than ten repeat measurements as in Harvey et al. (2001 a, b). However, the consistency in the RE and CV over a range of silhouette lengths suggest that these results could be used as measures of the accuracy and precision of stereo-video measurements made on fish in the field. Furthermore, the measurement of these points closely resembles the typical relationship for the cameras and the subjects of any potential field measurements of reef fish that would be made with the stereo-system.

By comparing SCUBA diver estimates of fish length to measurements of the same fish by a stereo-video, it is possible for the first time, to determine the accuracy and precision of SCUBA divers' length estimates of living, mobile reef fish. In doing this, field estimates of the RE and CV from the stereo-video are used to provide 95% confidence limits for the true fish length, and so obtain bounds on the divers' errors.

Therefore, this paper has 3 aims:

1. to determine the accuracy and precision of stereo-video measurements of fish while they are swimming;
2. to determine the accuracy and precision of diver length estimates of reef fish made under field conditions using stereo-video measurements as an accurate indicator of true length;
3. to predict the statistical power of experienced scientific divers to detect changes in the mean length of three common species of reef fish from around the coast line of New Zealand.

METHODS

Stereo-video measurements of the length of real fish

On 16 April 1998 measurements were made of the fork length of seventeen fish of distinctive length and species before the fish were released into a large saltwater aquarium (Table 1). These fish were then recorded by a stereo-video system in situ with ninety three individual recordings made.

Diver estimates of fish length

Comparisons of lengths estimated by three experienced diver scientists were made in the field during 1996 in Milford Sound, a fiord on the south west coast of New Zealand. Simultaneous diver / stereo-video length estimates were made possible through the use of a Technisub fullface mask containing a waterproof microphone.

The fullface mask and microphone were linked by a 3 m cable into one of the video cameras allowing the observers wearing the mask to record their length estimates onto the sound track of the videotape. The divers estimating the length of reef fish swam directly above, and slightly in front, of the stereo-video system to ensure that their view of the fish was not obscured by the stereo-video, or the bubbles from the diver operating the camera rig. The divers estimated the lengths of six species of fish. (*Latris lineata*, *Nemadactylus macropterus*, *Aplodactylus arctidens*, *Parapercis colias*, *Notolabrus celidotus*, *Notolabrus fucicola* and *Pseudolabrus miles*) all of which are common around the southern coast of New Zealand. The dates of dives, an estimate of the horizontal visibility, and the number of comparative measurements made per dive are presented in Table 2.

ANALYSIS OF VIDEO TAPES AND DATA

Analysis of video tapes

Video tapes of diver and stereo-video length estimates were processed by viewing the images through a Sony VCR linked to a PC frame grabber. Paired frames were selected and grabbed only when it was very clear that there could be no confusion over the fish identified by the diver and the fish seen on the video imagery. An additional criterion for stereo-video measurement was that the fish had to be at an angle of less than approximately 50 degrees perpendicular to the stereo-video cameras to ensure maximum accuracy (Harvey and Shortis, 1996). Selected images were then imported into a stereo-photo comparator and the fork length of the fish measured by locating the fork of the tail and the snout of the fish in the left and right images with a screen cursor controlled by the mouse. A more detailed explanation of the stereo-photo comparator and the stereo-video system can be found in Harvey and Shortis (1996).

DATA ANALYSIS

Stereo-video measurements of fish in an aquarium

The accuracy and precision of the stereo-video measurements of the fish placed in the aquarium were summarised by calculating the mean error, the mean relative error and the coefficient of variation (CV) of the length estimates.

Diver versus stereo-video data

The error and relative error (RE) of the length estimates made by each diver was estimated by assuming the true length of the fish was the same as the measurement by the stereo-video. Relative error is defined here as the absolute difference between the measurement and the true value, divided by the true value to gain a proportional value. In this case the visual estimates are the measurements and the true value is provided by the stereo-video system. In order to provide bounds within which the true errors lie, 95% confidence limits for the true fish length were calculated as:

$$\text{Lower limit} = SV * (1 - 2\ CV)/(1 + RE)$$

$$\text{Upper limit} = SV * (1 + 2\ CV)/(1 + RE)$$

where SV is the stereo-video estimate of the length of a fish, CV is the coefficient of variation and RE the relative error of stereo-video length estimates. The values used were those based on a subset of measurements made in Harvey and Shortis (1998), namely RE = -0.34% and CV = 0.56%.

The relative error for diver estimates was calculated by:

diver estimate / stereo-video estimate - 1

The upper and lower relative errors for the divers was calculated by:

diver estimate / lower or upper stereo-video 95% confidence limits – 1

Bounds on the true error and relative error were then found by assuming the true length of the fish to be the value of the lower or upper 95% confidence limits. For example, the length of one of the fish was estimated to be 12.14 cm using the stereo-video, with 95% confidence limits being 12.04 cm and 12.32 cm. The diver's estimate was 13 cm, giving an estimated error of 0.86 cm and an estimated relative error of 7.1%. The lower and upper confidence limits for these errors, based on the stereo-video confidence limits, would therefore be 0.68-0.95 cm and 5.5-7.9% respectively.

The RE and CV for stereo-video error in Harvey et al. (2001a) are reasonably consistent across the recorded lengths. By using the mean RE and CV in our calculations, the data are applicable to a wider range of fish lengths, but also take into consideration the effect of a consistent bias in measurement accuracy. In this way the adjusted data represents a best case scenario for divers.

Power analysis

Our method for predicting power follows that outlined in Harvey et al. (2001b), and is based on modelling the variation in estimated length between replicate samples for a number of fish seen at two or more sites. This variation has four components, namely that between:

- sites in the true mean length of reef fish
- the true sizes of fish within each site

- measurements of the same fish by different SCUBA divers or by a stereo-video system
- measurements of the same fish by one SCUBA diver or by a stereo-video system

The first two of these components were estimated from trawl and pot data collected by New Zealand's Ministry of Fisheries on populations of blue cod (*Parapercis colias*), red cod (*Pseudophycis bachus*) and snapper (*Pagrus auratus*) from around New Zealand. The distribution of the samples and the mean lengths of the fish collected at each site are shown in Figure 1 of Harvey et al. (2001b). The last two components of the power analysis differ from those used in Harvey et al. (2001b) in that they are based on the relative errors (error/known length) of length estimates recorded in the field for stereo-video from Harvey and Shortis (1998) and those of length estimates of reef fish made by experienced diver scientists as described in this paper. Additionally, where calculations from Harvey et al. (2001b) were based on ten repeat measurements of a silhouette by a stereo-video, these calculations are based on only one measurement. The average of a number of repeat measurements for the stereo-video would decrease the CV and RE for field data (Fig. 1) resulting in more accurate and precise estimates.

RESULTS

Stereo-video measurements of the length of real fish

Stereo-video measurements of fish swimming in the aquaria produced accurate and precise estimates of the fork length of the fish (mean error of -0.04 cm, std dev = 0.31 cm, CV = 0.7%, SE = 0.03 cm). All recordings of the fish were made at distances of between 2.66 and 4.16 m from the stereo-video system (mean = 3.21 m) with visibility being estimated at 5 m. These results are very similar to those obtained for stereo-video field estimates which were used to calculate the RE, CV and confidence limits, against which to compare divers estimates. These results are based upon measurements of fish when their bodies were straight. However, some species of fish swim with an exaggerated sinusoidal movement, making straight-line measurement virtually impossible. Eleven sets of measurements were made of a single *Squalus acanthias* (dogfish, fork length 45 cm) whilst it was turning. A series of measurements made between clearly identifiable features (dorsal and caudal fins) along the length of the body were added together to measure the fork length of the fish. These measurements were slightly less accurate and precise than those for straight bodies (mean error = -0.39 cm, RE = -0.88%, CV = 2.2%).

Diver estimates of fish length

The distances over which the three SCUBA divers made their estimates were comparable. Diver 1 estimated fish lengths at distances between 2.4-6.3 m (mean = 3.41 ms), diver 2 between 2.67-5.97 m (mean = 3.88 m) and diver 3 between 2.38-6.35 m (mean = 3.68 m). Figures 2, 3 and 4 show the distribution of the error for each diver. The accuracy of diver length estimates was high with the mean error ranging from 0.81 cm for diver 1 to 1.44 cm for diver 2 (Table 3).

When the diver estimates were adjusted to take into consideration the 95% confidence limits for the stereo-video error, mean SCUBA diver error was less than 1 cm. This figure supports claims by Jennings et al.(1996) of mean length estimation error of 3.1% for fish in the range 8-35 cm. In this study the length of the fish, as measured by stereo-video, ranged from 8.5 to 53 cm in length. Although the mean accuracy is high, the mean precision of the SCUBA divers' length estimates is poor, as shown by the standard deviations and standard errors (Table 3). This is consistent with the high relative errors (Table 4). Plots of the range of error against the length of the fish as measured by stereo-video for each diver (Fig. 2, 3, 4) show that diver 1 had a reasonably consistent range of error, whilst divers 2 and 3 both tended to overestimate the length of smaller reef fish and underestimate the length of the larger reef fish.

Power analysis

The determination of the accuracy and precision of experienced scientific SCUBA divers' length estimates in the field allowed us to predict their theoretical power to detect changes in the mean length of populations of blue cod (*Parapercis colias*), red cod (*Pseudophycis bachus*) and snapper (*Pagrus auratus*) from around New Zealand coastal waters. Based on recording 30 length estimates of blue cod per sample ($\alpha = 0.05$), these experienced scientific divers would need to record 36 samples per site to detect a 15% change in the mean length of a population with 95% power. In comparison, 12 samples would need to be collected with a stereo-video system (Figure 5). Nearly identical results are recorded for snapper with a 15% change in the mean length being detected (95% of the time) with 36 samples by experienced scientific divers as opposed to 13 samples with stereo-video. Red cod show greater spatial variability in the mean length of populations than either blue cod or snapper and, therefore require larger sample sizes to detect even large (40%) differences in the mean length of a population. To detect a 15% change in the mean length of a population of red cod with 95% power ($\alpha = 0.05$) requires experienced scientific divers to record 60 samples per site while 37 are required by stereo-video (Fig. 6). Thus for monitoring programs that aim to detect changes in the mean length of fish that are rare, or are sampled in low densities, stereo-video has many advantages. For example, if only 1 blue cod were recorded per sample, stereo-video would detect a

15% change in the mean length of the population with 95% power ($\propto = 0.05$) using 37 samples per site. An experienced scientific diver would need to collect 170 samples to detect the same change with 95% power (Fig. 7).

DISCUSSION

The accuracy and precision of stereo-video measurements of reef fish swimming in a saltwater aquarium agreed very closely with those obtained from static field measurements. Additionally, repeated measurements of a calibration check plate through the duration of the 13 dives made in the field show that there is little variation in the accuracy and precision of measurements made with the stereo-video system within any one particular dive (Harvey and Shortis, 1998). Therefore, it is valid to use the upper and lower 95% confidence limits from stereo-video measurements to determine the errors of SCUBA diver length estimates of fish in the field.

The results show that there is a large amount of variation in the precision of estimates made by the experienced scientific divers used in this research. This must be of concern, especially if length estimates are to be used to estimate biomass or fecundity. In fish, fecundity is directly related to size (Alm, unpublished 1959) and body weight of individuals can range across four orders of magnitudes (Werner and Gillian, 1984). Therefore, even small errors in the length estimate could have a large influence on weight estimates. For example based on length weight relationships published in Taylor and Willis (1998) a blue cod 180 mm in length weighs 77.5 grams. An 8 mm error could result in the true weight of the fish being between 66.5 gms (172 mm) and 89.7gms (188 mm). For fish with an exponential length / weight relationship the effects of error in length estimates becomes more significant when estimating the lengths of larger fish. Based on Taylor and Willis (1998) a snapper (*Pagrus auratus*)

600 mm in length would weigh 4134 gms. An 8 mm error could result in the true weight of the fish being between 3981.6 gms (592 mm) and 4289.5 gms (608 mm). If the 95% confidence intervals of the divers measurements (+- 105.8 mm) are used the usefulness of visual length data collected by divers becomes questionable. As the accuracy of estimates decreases, the biological differences measured, in either relative or absolute terms, become more difficult to detect.

Although there are differences in the mean errors recorded by each diver, there is little difference between the relative errors recorded within the divers over all of their measurements. Therefore, in contrast to the work of Harvey et al., (2001b), these results are applicable not only to monitoring programs involving multiple researchers, but also to those that involve a single researcher undertaking all the observations throughout the duration of the program. It is also possible that the variability between divers is masked by the low number of divers participating in the research.

The results show that stereo-video can be used to make accurate field measurements of the length of reef fish, and that variation in the accuracy and precision of experienced diver scientists length estimates decreases the confidence in such estimates. This is particularly of concern if the data are to be used to make spatial and temporal comparisons between and amongst populations of fish (e.g. reserve versus non-reserve). The advantages of using a stereo-video will vary depending on the size of the effect to be detected, the desired level of power and variance in the mean lengths of populations of fish selected for monitoring between different sites. Recently Kulbicki (1998) has called for investigations into new ways of assessing the density and biomass of reef fishes using underwater visual census techniques. Underwater stereo-video is clearly one such option.

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Table 1.

Species	Length (cm)
Aplodactylus arctiden	40
Helicolenus papillosus	32 (2 fish)
Latris lineata	36.5, 38, 40, 42, 46
Notolabrus celidotus	18‡, 21.5‡, 25†, 28.5‡, 30†
Parapercis colias	37
Squalus acanthias	41, 45, 59

Table 2.

Diver	Dive #	Date	Dive time (min)	Visibility (m)	# of fish
Diver 1	1	23/4/96	27	10	38
Diver 1	2	23/4/96	37	11	50
Diver 1	3	24/4/96	33	9	30
Diver 1	4	30/10/96	30	6	43
Diver 1	5	30/10/96	35	6	34
Diver 2	1	20/4/96	29	10	58
Diver 2	2	20/4/96	33	10	33
Diver 2	3	21/4/96	32	10	55
Diver 2	4	21/4/96	35	8	32
Diver 2	5	21/4/96	34	8	31
Diver 3	1	30/10/96	40	6	77
Diver 3	2	30/10/96	42	6	64
Diver 3	3	30/10/96	50	6	56

Table 3.

Units (cm)	Error	Std dev	Std err	Error Lower	Std dev Lower	Std err Lower	Error Upper	Std dev Upper	Std err Upper
Diver 1	0.81	4.46	0.32	0.54	4.51	0.32	0.96	4.44	0.31
Diver 2	1.44	6.33	0.45	1.11	6.41	0.45	1.62	6.29	0.44
Diver 3	1.25	4.91	0.35	0.96	4.97	0.35	1.40	4.88	0.34

Table 4.

	RE	RE Lower	RE Upper
Diver 1	8%	7%	9%
Diver 2	16%	14%	17%
Diver 3	11%	10%	12%

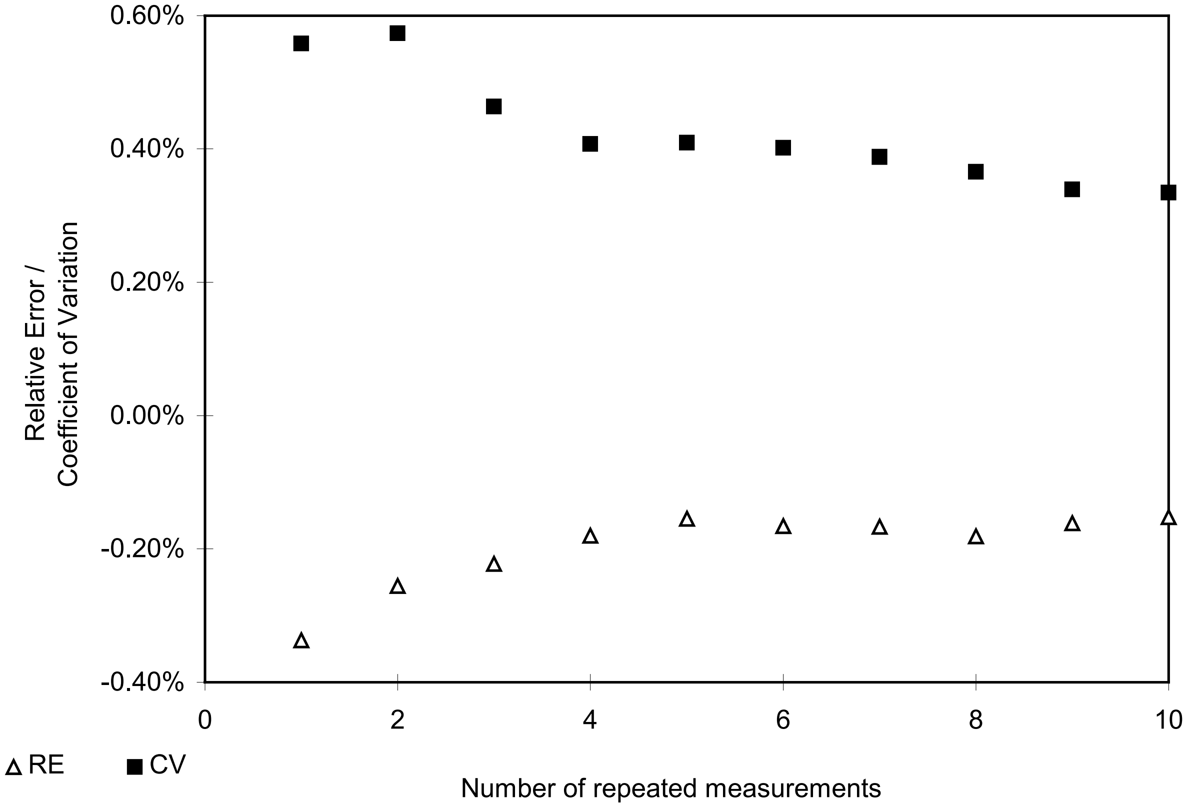
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
Relative Error / Coefficient of Variation
0
2
4
6
8
10
Number of repeated measurements
△ RE
■ CV

Figure 1.

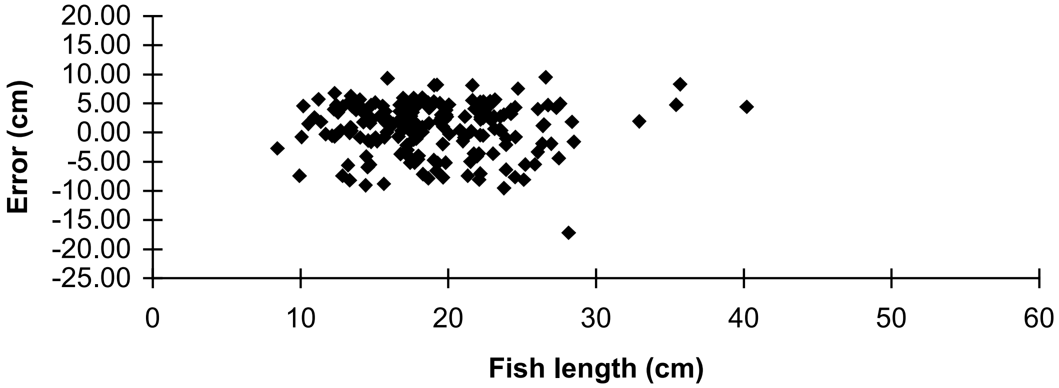
Error (cm)
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
0
10
20
30
40
50
60
Fish length (cm)

Figure 2.

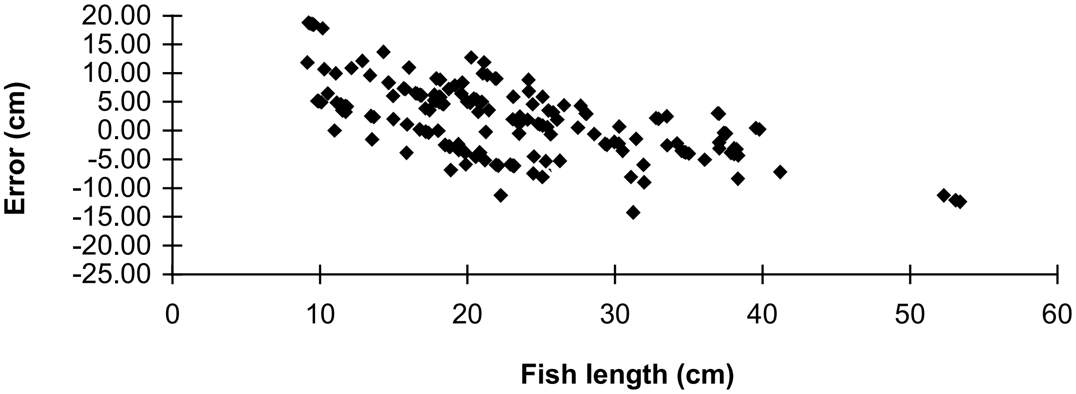
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
Error (cm)
0
10
20
30
40
50
60
Fish length (cm)

Figure 3.

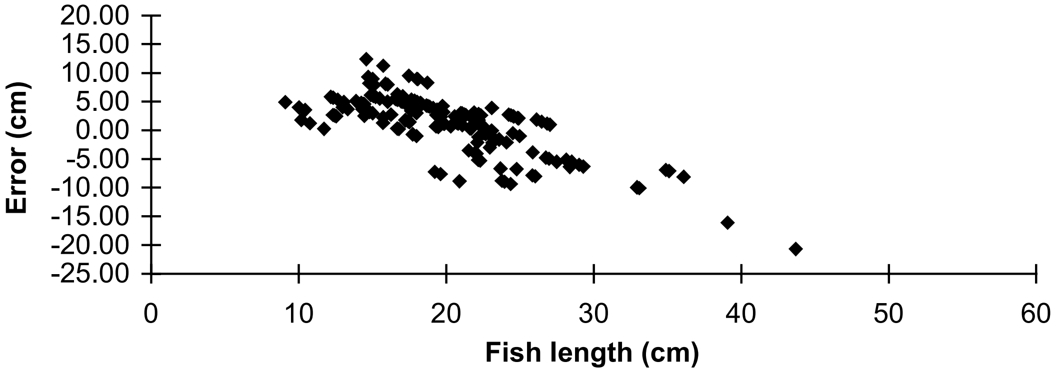
20.00
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
Error (cm)
0
10
20
30
40
50
60
Fish length (cm)

Figure 4.

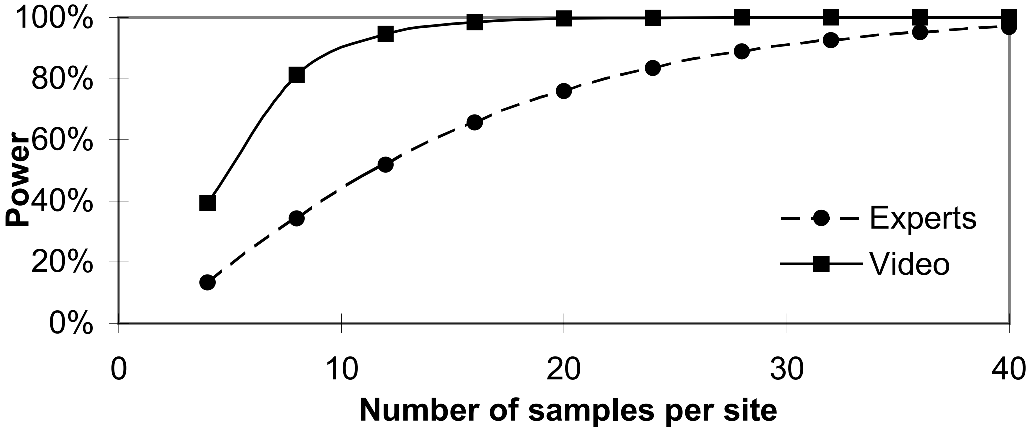
100%
80%
60%
40%
20%
0%
Power
0
10
20
30
40
Number of samples per site
Experts
Video

Figure 5.

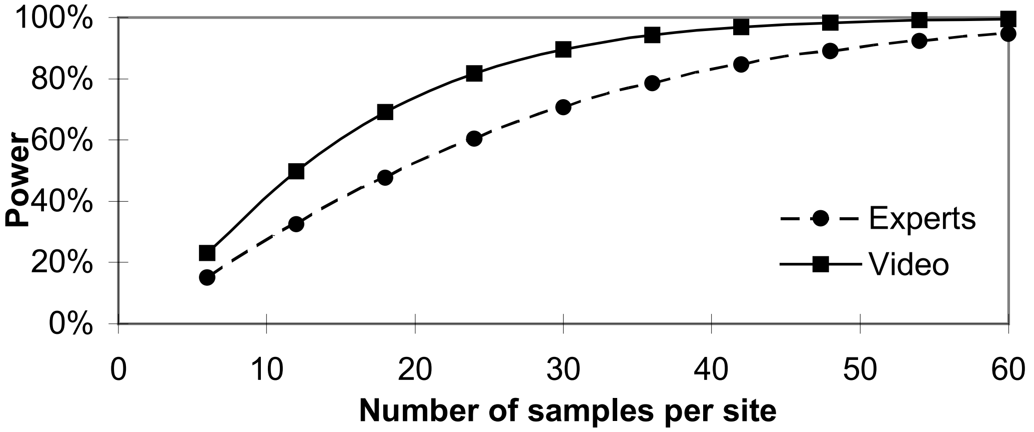
100%
80%
60%
40%
20%
0%
Power
0
10
20
30
40
50
60
Number of samples per site
Experts
Video

Figure 6.

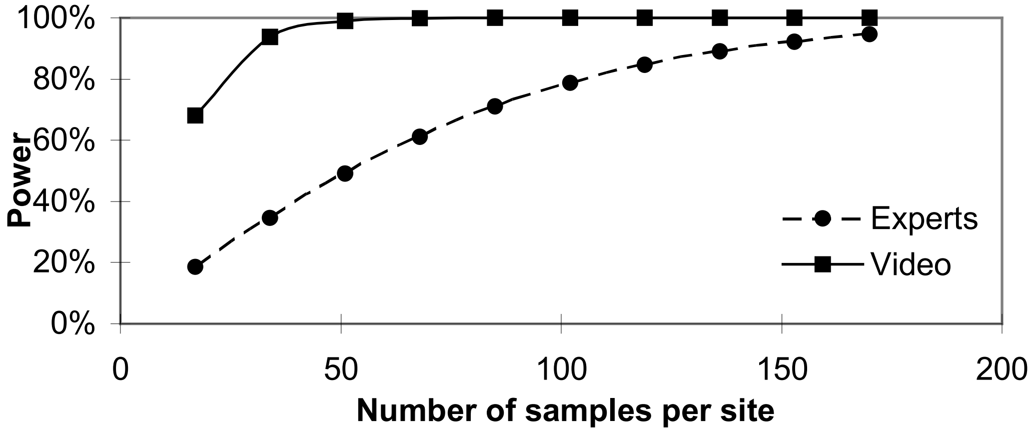
100%
80%
60%
40%
20%
0%
Power
0
50
100
150
200
Number of samples per site
Experts
Video

Figure 7.

Table 1. The fork length and species of fish measured with stereo-video. †= male, ‡=female

Table 2. The number and duration of dives undertaken by each diver. Visibility and numbers of fish recorded per dive are also included.

Table 3. Estimates of the accuracy and precision of diver field estimates, with 95% confidence limits. N=200

Table 4. Estimates of the relative error of diver field estimates, with 95% confidence limits. N=200

Figure 1. Effect of repeated measurements on the relative error and coefficient of variation of stereo-video measurements.

Figure 2. Distribution of Error for Diver 1.

Figure 3. Distribution of Error for Diver 2.

Figure 4. Distribution of Error of Diver 3.

Figure 5. The power of experienced scientific divers and a stereo-video to detect a 15% change in the mean length of a population of blue cod. (30 fish per sample, Alpha = 0.05)

Figure 6. The power of experienced scientific divers and a stereo-video to detect a 15% change in the mean length of a population of red cod. (30 fish per sample, Alpha = 0.05)

Figure 7. The power of experienced scientific divers and a stereo-video to detect a 15% change in the mean length of a population of blue cod. (1 fish per sample, Alpha = 0.05)