Abstract–We calculated the power of visual length estimates by novice and experienced scientific SCUBA divers and estimates generated by a stereo-video system to detect changes in the mean length of three common species of reef fish from New Zealand. Length estimates from a stereo-video system had much greater power for blue cod (mean length=33.1 cm., range 19.5–50.1 cm.) and snapper (mean length=31.7 cm., range 23–71 cm.). For a third species, red cod (mean length=42.5 cm., range 13–74 cm.), the statistical power of diver and stereo-video estimates was much less for an equivalent number of samples owing to the greater variation in the true mean length of red cod recorded at different sites. At 90% power, a stereo-video system detected a 15% (~5-cm) change in the mean length of blue cod with 63% less samples (10) than those required by the experienced scientific divers (27). Novice scientific divers required 28 samples.

Improving the statistical power of length estimates of reef fish: a comparison of estimates determined visually by divers with estimates produced by a stereo-video system

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Visual censuses of reef fish have been used to monitor fish communities as indicators of environmental degradation (Hourigan et al., 1988; Fausch et al., 1990) and as a fisheries management tool for assessing the condition of reef fish stocks (Ault et al., 1998). Ault et al. (1998) used data on the average length of a fish stock as an index of fishing effects. Information on the length frequency or mean length of a fish population when linked with even a rudimentary knowledge of the biology of the species may allow estimates of recruitment to the adult population, fishing intensity, and rates of recovery from fishing (McCormick and Choat, 1987).

Environmental surveys commonly use SCUBA divers to count and visually estimate the length of individual reef fish (Jones and Chase, 1975; Harmelin-Vivien and Bouchon-Navaro, 1981; Bellwood and Alcala, 1988; Samoilys, 1989; English et al., 1994). These visual censuses have many advantages in comparison with other sampling techniques: they are quantitative, quick, nondestructive and repeatable (English et al., 1994). Visual census techniques have been widely adopted and are used to monitor changes in the relative abundance or mean length of reef fish within marine protected areas (Bell, 1983; McCormick and Choat, 1987; Alcala, 1988; Cole et al., 1990; Francour, 1991, 1994; Russ and Acala, 1996) and as a tool for assessing the standing stock or biomass of individual species of reef fish (Craik, 1981; Russ, 1985; Medley et al., 1993; Polunin and Roberts, 1993; Hart et al., 1996). Biomass is estimated from the relationship between length and the weight of an individual fish of a certain species (Kulbicki, 1989; Kulbicki et al.,1993). However, the question not yet addressed is how useful are data from visual length estimates for detecting changes in the mean length or length frequency of a population of reef fish?

The advantages of assessing the statistical power of environmental monitoring programs has been discussed by

a number of authors (Green, 1979; Andrew and Mapstone, 1987; Gerrodette, 1987; Hayes, 1987; Peterman, 1990a, 1990b; Fairweather, 1991). Statistical power is defined as the probability of correctly rejecting a null hypothesis and is $1-\beta$, where β is the probability of a type-II error (Andrew and Mapstone, 1987; Gerrodette, 1987; Fairweather, 1991). An example of a type-II error in environmental monitoring would be to conclude that no impact has occurred when one has. Therefore, low statistical power can be disastrous for environmental monitoring because adverse environmental impacts go undetected (Fairweather, 1991). Despite this problem, few marine ecologists and biologists make use of power analysis (Fairweather, 1991). Power analysis has been used to determine the optimum size of sample units and levels of replication needed to detect an effect of a particular size with a desired level of probability (Andrew and Mapstone, 1987; Gerrodette, 1987; Fairweather, 1991). Power is a function of sample size, the probability of a type-I error (α) and the effect size (Gerrodette, 1987). Fairweather (1991) discussed the issues associated with deciding upon an appropriate level of power. Low power can be attributed not only to the sample design, but also to biases and errors inherent in the sampling method (Andrew and Mapstone, 1987) and power analysis must account for the uncertainty of measurement error (Gerrodette, 1987).

Historically, reef-fish ecologists have failed to calculate and publish the power of their sampling programs. Furthermore, it is frequently assumed by many researchers that their visual estimates of reef-fish length are both accurate and precise. In the published literature on reef fish studies containing data on visual length estimates, we found only three examples out of forty-three papers in which the authors stated the accuracy of their *in situ* visual length estimates (Sweatman, 1985; Polunin and Roberts, 1993; Green, 1996).

The aims of our study were 1) to examine the accuracy and precision of length estimates made by a number of experienced and novice scientific SCUBA divers, and so determine their power to detect changes in the mean length of populations of three common species of reef fish from around New Zealand coastal waters and 2) to demonstrate that the power to detect changes in mean length can be greatly improved for two of the three species by using an underwater stereo-video system instead of divers' visual estimates.

The three fish species that we consider are blue cod (*Parapercis colias*), red cod (*Pseudophycis bachus*), and snapper (*Pagrus auratus*). All three species support commercial trawl (red cod and snapper), long line (snapper), and trap (blue cod) fisheries. Blue cod and snapper are also the focus of popular recreational fisheries and thus are important species in New Zealand.

Methods and materials

To assess the extent to which measurement error will affect the power of visual estimates to detect changes in mean length of a population of fish, we considered the fol-

lowing simple scenario. Suppose we are interested in comparing the mean lengths of two fish populations and we collect length estimates by randomly selecting dive locations within each site. At each location, the dive involves the visual collection of data from a strip-transect or point-count method to measure the length of each of a number of fish of the species concerned. Later, we will assume that the same numbers of fish are encountered on each dive. This is clearly unrealistic because the numbers encountered will obviously differ: it merely helps to simplify the discussion of power analysis. The analysis we consider here involves first transforming the estimated lengths by using natural logarithms, calculating the mean log-length at each location in each site, and then comparing sites by a standard *t*-test, with the locations acting as replicates. The reason for considering log-length rather than length is twofold. First, it may be more prudent to perform such an analysis on the log-scale, for the usual reason of wanting to satisfy the assumptions of the *t*-test. Second, the power analysis can then be framed in terms of our ability to detect a percentage change in mean length. As a consequence, the standard allometric relationship between log-length and log-weight (Kulbicki, 1989) implies that the results given here for the power to detect a percentage change in mean length will also apply to an equivalent proportional change in mean weight.

The estimated length of fish j at dive location i can be written as

$$y_{ij} = x_{ij}e_{ij},$$

where x_{ij} = the true length of the fish; and
e_{ij} = the relative accuracy of the estimate (see St John et al., 1990).

This equation shows that variation in estimated length will arise from two sources: first, from the natural variation, both between and within dive locations, of the true lengths of the fish; second, from the variation, between and within dives, in the relative accuracy of the estimate. It is this second component of variation that will be influenced by using stereo-video system as opposed to experienced or novice scientific divers. The relative magnitudes of the two sources of variation will determine the benefits to be expected from improving the measurement of length. Thus, if the natural variation in true length is large in relation to the measurement error, there will be little statistical benefit in reducing the latter.

On a log-scale this equation can be written as

$$\log y_{ij} = \log x_{ij} + \log e_{ij}$$

The variation in $\log x_{ij}$ between and within dive locations can be expressed in a one-way random effects model as

$$\log x_{ij} = a_i + b_{ij},$$

with $\mathrm{Var}(a_i) = \sigma^2_a$ and $\mathrm{Var}(b_{ij}) = \sigma^2_b$ (Sokal and Rolf, 1995). Thus σ^2_a and σ^2_b are the between-dive and within-dive variance components, respectively.

Now consider the variation in $\log e_{ij}$. We can write

$$e_{ij} = d_i \varepsilon_{ij},$$

where d_i = an effect applying to all estimates made during dive i; and

ε_{ij} = an effect applying solely to the estimate for fish j during that dive.

The value of d_i will be influenced by the conditions at location i, as well as by the diver used at that location. The value of ε_{ij} will be influenced by the activity of the fish and its orientation to the diver.

We can now write

$$\text{Log } e_{ij} = \log d_i + \log \varepsilon_{ij},$$

with $\text{Var}(\log d_i) = \sigma_d^2$ and, $\text{Var}(\log \varepsilon_{ij}) = \sigma_\varepsilon^2$, analogous to the equation for $\log x_{ij}$. Again, σ_d^2 and σ_e^2 are the between-dive and within-dive variance components.

The power analysis that follows involves predicting the variation we would expect in $\log y_{ij}$ for a given number of dive locations (n) and a fixed number of fish at each location (m). The equations above can be combined to show that this variation has four components. Because

$$\log y_{ij} = a_i + b_{ij} + \log d_i + \log \varepsilon_{ij},$$

we have

$$V(\log y_{ij}) = \sigma_a^2 + \sigma_b^2 + \sigma_d^2 + \sigma_\varepsilon^2.$$

Going one step further, the predicted variance of the mean of $\log y_{ij}$ over all fish (j) and all dives (i) at that site can be written as

$$V = \frac{\sigma_a^2 + \dfrac{\sigma_b^2}{m}}{n} + \frac{\sigma_d^2 + \dfrac{\sigma_\varepsilon^2}{m}}{n}.$$

Assuming the number of dives and fish recorded per dive is the same at the second site, the predicted power to detect a difference D in the mean log-lengths at the two sites is given by

$$F_\tau \left[\frac{D}{SED} - t_{a/2} \right],$$

where $F_\tau[.]$ = cumulative distribution function;

$t_{\alpha/2}$ = the upper $\alpha/2\%$ point for the t-distribution with $2(n-1)$ degrees of freedom, and SED = $\sqrt{2V}$, which is the standard error of the difference in the two mean log-lengths (see Sokal and Rohlf, 1995, p. 263). Note that if the analysis involved the comparison of $s>2$ sites, the degrees of freedom for the t-distribution would be $s(n-1)$. Because the analysis is on a log-scale, the difference D is calculated as $D=\log(R+1)$, where R is the percentage change of interest.

In order to evaluate the power, we needed estimates of the four variance components. The first two, σ_a^2 and σ_b^2, were estimated by using catch data on true length for populations of red cod, blue cod, and snapper from around New Zealand from trawl and trap surveys by the Fisheries Division of the National Institute of Water and Atmospheric Research. The length data for red cod and snapper came from a number of locations around New Zealand (Fig. 1). The depths at which these fish were collected ranged between 20 and 40 m. The locations at which they were collected were grouped into sites, such that two locations that were within approximately 30 km of each other were considered to be at the same site. For red cod, there were 12 sites, each with between two and four locations: at each location, lengths were recorded for between 12 and 20 fish. For snapper, there were six sites, two of which contained 14 locations, and the other four had just two locations each. At each location, lengths were recorded for between 10 and 91 fish. The log-lengths were then analyzed by using nested analysis of variance. Site and location were specified to be random factors, and location was nested within the site. The location and residual variance components were used as estimates of σ_a^2 and σ_b^2, respectively. The data for blue cod came from one site, at five locations off Stewart Island. There were between 47 and 51 fish lengths recorded per location. The log-lengths were analyzed by using analysis of variance, with location being specified as a random factor. The location and residual variance components were used as estimates of σ_a^2 and σ_b^2, respectively. The remaining two variance components, σ_d^2 and σ_ε^2 were estimated by using data on the measurement error of novice scientific divers, experienced scientific divers, and a stereo-video system. These errors were determined by using a simple testing procedure for calibrating diver estimates of the lengths of reef fish. Silhouettes of fish were placed in the water and their lengths estimated by following the methods of the GBRMPA (1979), Bell et al. (1985), and English et al. (1994). There were eight novice divers and six experienced divers, each of who swam five repeat transects. On each transect they estimated the length of sixteen silhouettes. The same procedure was used for the stereo-video estimates: for each image the estimate used was the mean of ten measurements. The novice divers and three of the experienced divers made their length estimates in a saltwater pool. For the stereo-video system and the other three experienced divers, measurements were made in a swimming pool. Definitions of novice and experienced scientific divers are the same as those given in Harvey et al. (2000), which contains a full presentation of the data and detailed description of the method used. A full description of the design and calibration of the system can be found in Harvey and Shortis (1996, 1998).

The novice and experienced diver estimates were both analyzed by using nested analysis of variance of the logarithm of the relative accuracy (estimated length divided by true length). Diver and silhouette were specified to be random factors, and silhouette was nested within diver. The diver and silhouette variance components were used as estimates of σ_d^2 and σ_ε^2, respectively. The stereo-video estimates were analyzed by using analysis of variance of the logarithm of the relative accuracy, and silhouette

was specified as a random factor. The silhouette variance component was used as an estimate of σ^2_ε. Note that for the stereo-video estimates, we took σ^2_d. This is because there should be no variation in the accuracy and precision of measurement made with a stereo-video system operated by different divers over different dives. Operators either swim the system along a transect or locate it in one area to record point counts. The operator has no control over the configuration of the camera system and cannot change any of the parameters; both these features of the system would preserve measurement accuracy and precision. Over the duration of one dive, and between several dives, the small variations in calibration stability that occur have minimal effect on the accuracy and precision of measurements (Harvey and Shortis, 1998). Harvey et al. (2000) have shown that very small variations in measurement accuracy (mean error –0.25 cm) may occur depending on the level of experience of the operators with the software used for making measurements from the images in the laboratory. To minimize this error, measurements where made where the orientation of a fish was less than 50 degrees perpendicular to the camera rig (Harvey and Shortis, 1996).

Results

The estimates of the variance components used in the power analysis are shown in Tables 1 and 2, together with their 90% confidence limits. Figure 2 shows the predicted power of visual estimates made by novice and experienced scientific divers and the predicted power of estimates made by a stereo-video system to detect a 15% change in the mean length of populations of blue cod, snapper, and red cod based on recording 30 fish per sample. Fifteen percent has been selected as an effect size because it represents a 5-cm change in the mean length of the population of blue cod used for our study. The results show that for each of the three species, the experienced scientific divers had greater power to detect changes than did novice scientific divers. However, for blue cod and snapper (Fig. 2), the stereo-video system had much greater power to detect changes in the mean length than either novice or experienced scientific divers. For example, we could achieve 90% power to detect a 15% change in the mean length of blue cod by recording 10 samples per site with the stereo-video system, with 27 samples per site for experienced scientific divers, and with 28 samples per site for novice divers. Similar conclusions apply to snapper with 11, 23, and 29 samples being required, respectively, under the same conditions. The advantage of the stereo-video system was not as good for red cod (30, 43, and 50 samples, respectively) as a result of the greater variability in their true mean length between locations than that recorded for the other two species (Fig. 2).

Influence of effect size

Around the southern coastal waters of New Zealand, blue cod may reach a maximum size of 50 cm, averaging 20–30
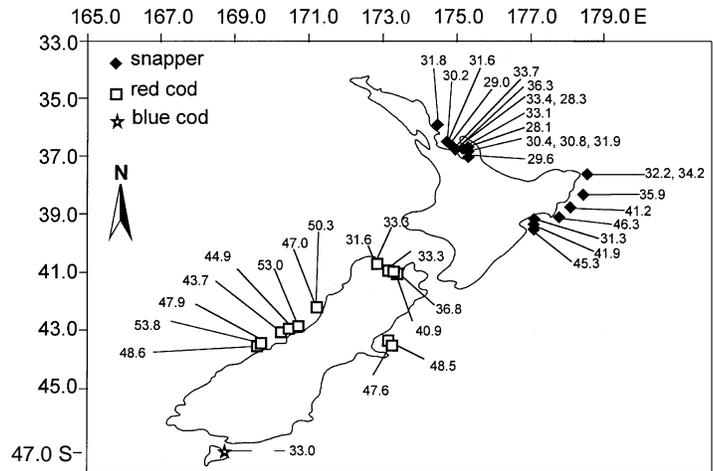
Figure 1

Map of the distribution of sites where fish were collected. The mean lengths shown for each site are in cm.

Table 1

Estimates of the variance components σ^2_a (between dive locations) and σ^2_b (within dive locations) of the natural logarithm of true fish length, for each of three species (90% confidence limits shown in parentheses).

Species	Between dive locations		Within-dive locations	
Red cod	0.025	(0.015,0.060)	0.076	(0.068,0.084)
Snapper	0.008	(0.005,0.014)	0.027	(0.025,0.029)
Blue cod	0.008	(0.004,0.060)	0.019	(0.016,0.022)

cm. (Ayling and Cox, 1982). The sample of blue cod on which our power analysis was based had a mean length of 33 cm. A 15% change in mean length would represent a change of 5 cm. Figure 3 shows how the advantages of stereo-video measurements over diver estimates diminish as the size of the change to be detected increases. For example, to detect a 30% change in the mean length of blue cod with 90% power 4 samples were needed per site with the stereo-video system, 9 samples were needed with experienced scientific divers, and nine samples with novice scientific divers. A 50% change would be detected with 90% power with three samples per site with the stereo-video system, five samples with experienced scientific divers, and five samples with novice scientific divers.

The influence of numbers of fish per sample

As the numbers of fish recorded per sample decreases (for example from 30 to 10 to 1), the number of samples that need to be recorded to maintain an equivalent level of power increases. For example, to detect an effect size

Table 2

Estimates of the variance components σ^2_d (between divers) and σ^2_ε (within divers) of the natural logarithm of relative accuracy (estimated length/true length), for experienced scientific divers, novice divers, and the stereo-video system (90% confidence limits shown in parentheses). The value of σ^2_d is taken to be zero for the stereo-video system.

	Between divers		Within divers	
Experienced divers	0.015	(0.006,0.067)	0.022	(0.017,0.030)
Novice divers	0.016	(0.008,0.063)	0.023	(0.017,0.031)
Stereo-video system			0.00020	(0.0001,0.0005)
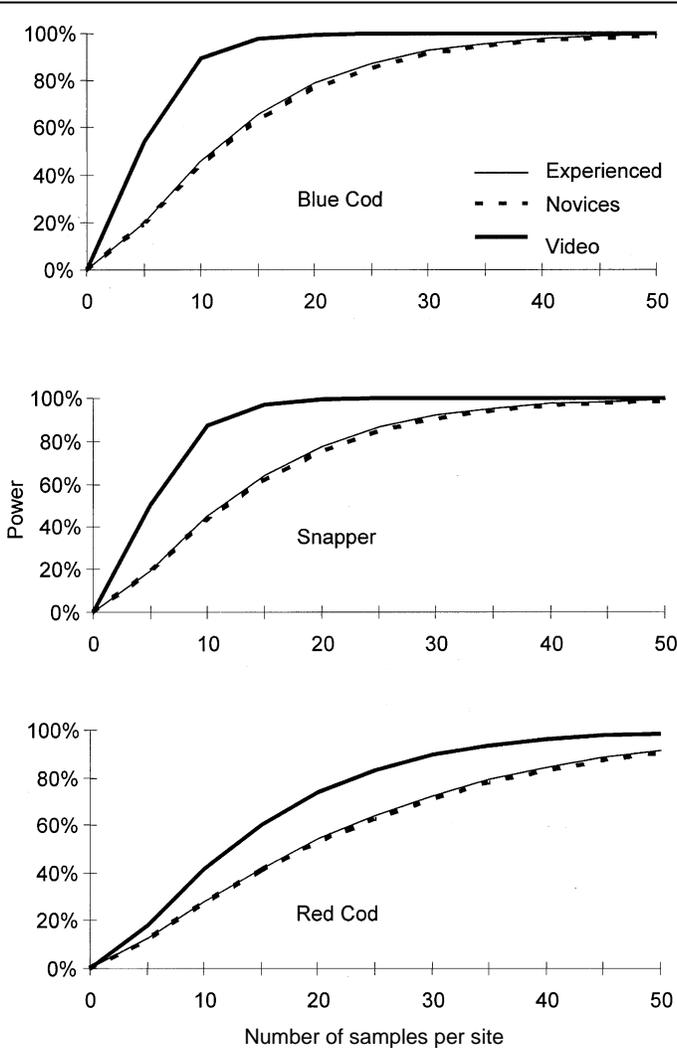
Figure 2

The power of novice scientific divers, experienced scientific divers and a stereo-video system to detect a 15% change in the mean length of a population of blue cod, snapper, and red cod. $n = 30$ fish; $\alpha = 5\%$.

of 15% with 90% power for blue cod when only one fish is being recorded per sample, 30 samples per site need to be recorded with the stereo-video system, 70 with experienced scientific divers, and 71 with novice scientific divers. When 30 fish are recorded per sample only 10, 27, and 28 samples are required, respectively (Fig. 4).
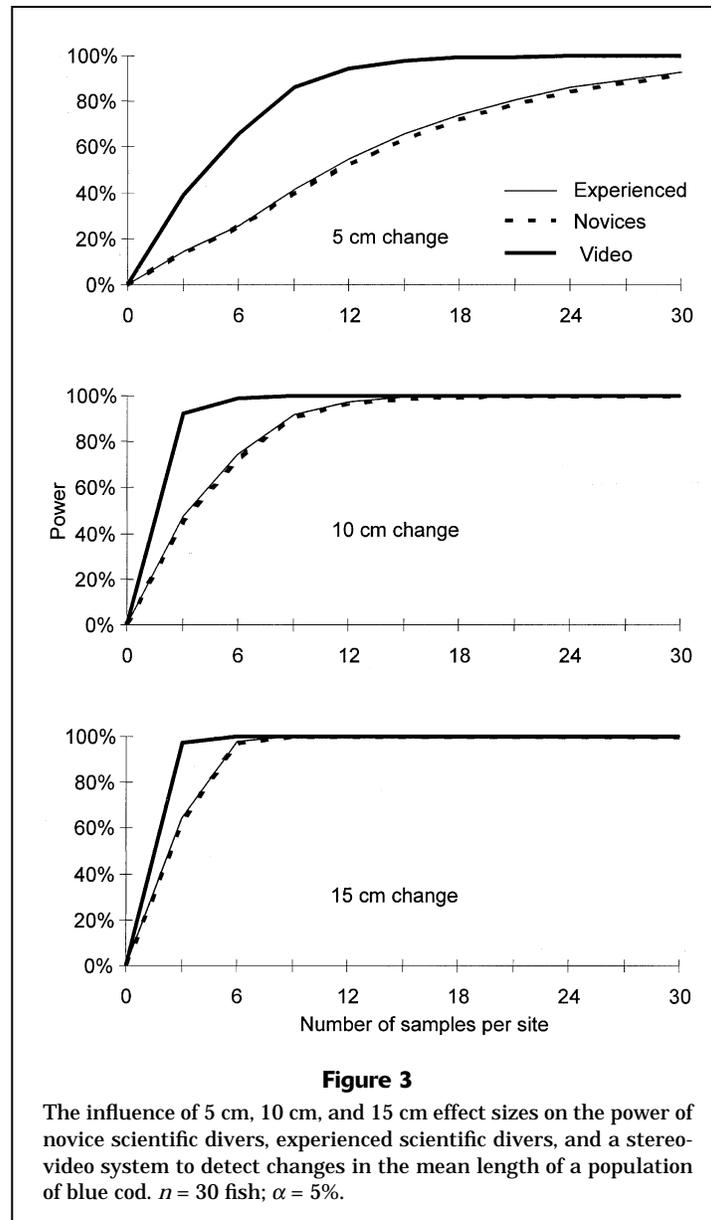
Influence of α

With stereo-video measurements, an increase in the value of α has little effect on the number of samples required to achieve a high level of power. When α is set at 5%, 10%, and 20%, we required 10, 9, and 7 samples per site, respectively, to detect a 15% change in the mean length of our population of blue cod with 90% power (Fig. 5). To achieve a similar level of power with experienced scientific divers 27, 22, and 17 samples needed to be recorded per site, whereas 28, 23, and 18 samples were required for novice scientific divers.

Discussion

Our research suggests that the power to detect changes in the mean length of three common species of fish from coastal waters of New Zealand will be higher when length estimates are made by a stereo-video system rather than by experienced or novice scientific divers. In addition, the level of power to detect these changes will differ between species, depending on the natural variability in mean length between different sites and locations. Managers and environmental researchers need to be aware of this issue when selecting suitable species of fish to be included in monitoring programs. For some species of fish (e.g. red cod), the variability in mean length between sites may be so great that even with a stereo-video system, unrealistically large numbers of samples need to be taken per site to detect changes in the order of 30% with high statistical power.

A stereo-video system may have many advantages in monitoring programs, particularly where few fish are recorded per sample. Fewer samples need to be taken per site with a stereo-video system to obtain an equivalent level of power compared with the number of samples needed with experienced scientific divers (Fig. 2), thus both time and money are saved in the field.

Even though calibration procedures are recommended and used by some researchers (GBRM-PA, 1979; Bell et al., 1985; Polunin and Roberts, 1993; Darwall and Dulvy, 1996), interdiver variability and diver measurement error may still invalidate comparisons of the changes in the mean length between sites and over time. Consequently, it is important that the level of precision and accuracy of length estimates is stated in reports and

Figure 3

The influence of 5 cm, 10 cm, and 15 cm effect sizes on the power of novice scientific divers, experienced scientific divers, and a stereo-video system to detect changes in the mean length of a population of blue cod. $n = 30$ fish; $\alpha = 5\%$.
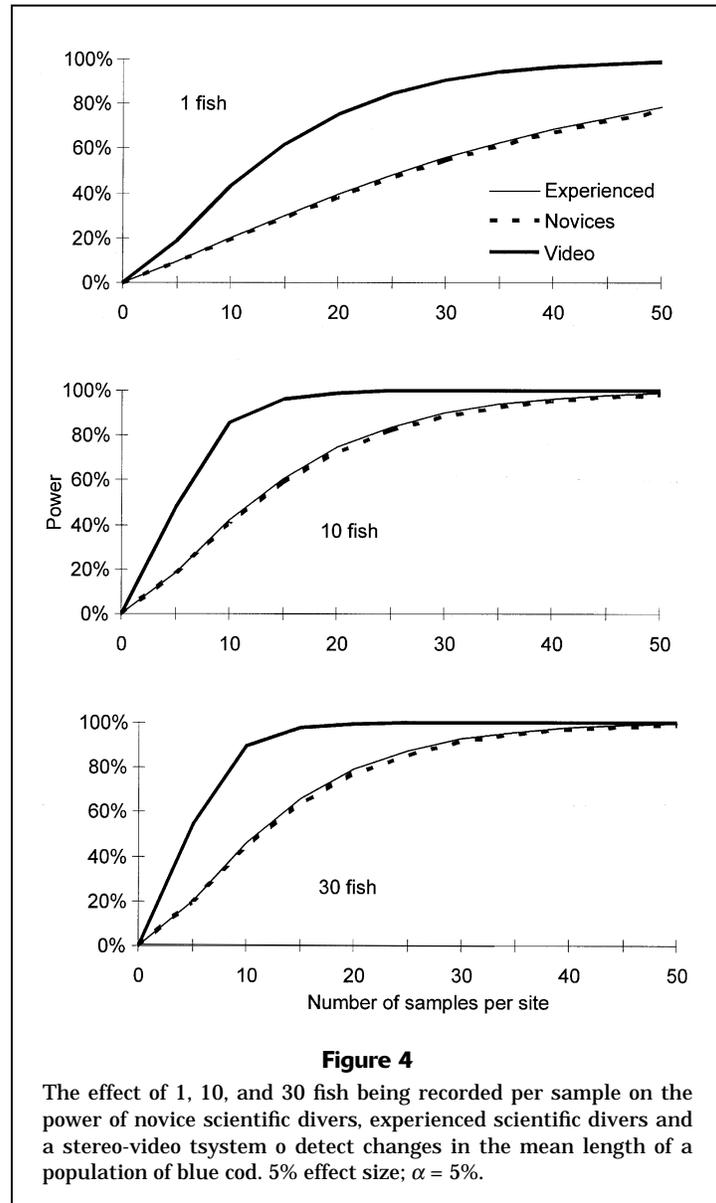
publications and that measurement error is minimized to allow realistic interpretation of the data and comparisons of assemblages or individual species. Because of these errors and biases, it is likely that many studies lack the statistical power to detect small, but biologically important, changes in fish length within reef-fish communities.

Increasing numbers of volunteers are assisting with sampling for monitoring programs, particularly in third world countries (Halusky et al., 1994; Mumby et al., 1995; Darwall and Dulvy, 1996). Darwall and Dulvy (1996) noted that the advantages of using volunteers in surveys include not only greater manpower, enabling large spatial surveys, but also financial savings and increased public awareness of environmental issues through participation.

To overcome the problem of subjectivity in visual estimates and to enhance the accuracy and precision of length estimates, and ultimately the power of a monitoring program, an underwater stereo-video system could be used. The use of an underwater stereo-video system provides an opportunity for volunteers to be involved in monitoring programs without compromising the quality of the data.

In assessing the statistical precision of visual length estimates, we have focused solely on the extra variability in the estimates introduced by measurement error. This error can also introduce a bias in the estimates. For example, the experienced scientific divers used by Harvey et al. (2000) had a mean relative error of –8.6% (SE=1.9%), suggesting that they would on average underestimate the true length by between 5% and 12%. In the type of study for which we have predicted the power to detect a difference in mean length, this bias will make little, if any, contribution to the loss of precision because the true lengths

Figure 4

The effect of 1, 10, and 30 fish being recorded per sample on the power of novice scientific divers, experienced scientific divers and a stereo-video tsystem o detect changes in the mean length of a population of blue cod. 5% effect size; $\alpha = 5\%$.

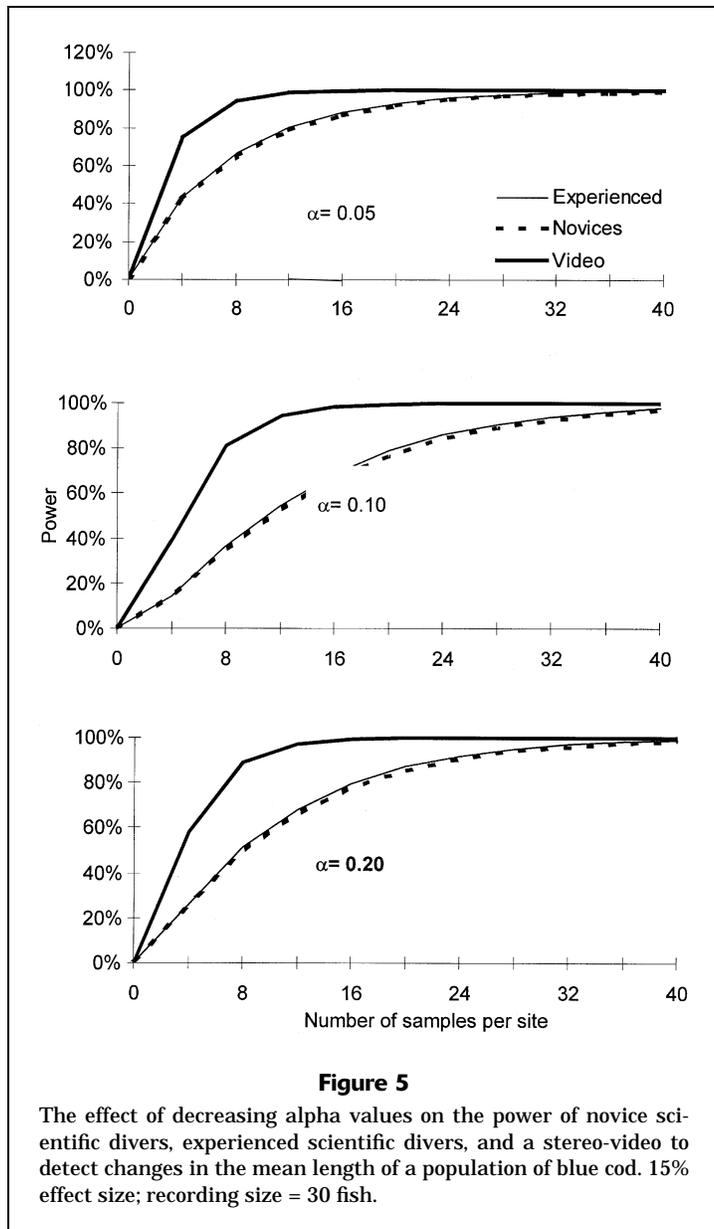will be tend to be underestimated by the same amount at the two sites.

For clarity of exposition, we have considered only the simplest possible study in which mean lengths of size-frequency distributions might be compared. We would expect that, at least qualitatively, the power comparisons made in our study would apply equally to other, more complex, sampling designs. Likewise, the focus of our study has been on mean length (and thereby biomass), but we conjecture that the benefits of using a stereo-video system will apply equally well for the comparison of size-frequency distributions.

Our calculations are based on length estimates made by divers and a stereo-video system in a controlled environment with plastic silhouettes. Under field conditions with moving fish, variable light conditions, and with other objects such as corals or kelps in the field of view providing a

scale, diver and stereo-video estimates may be more or less accurate and precise, and thus change the power analysis.

Conclusion

A stereo-video system provides a new and alternative method for collecting length data on reef fish through nondestructive visual sampling. The use of a stereo-video system reduces measurement error substantially, thus increasing the statistical power of a monitoring program to detect changes in the mean length of a population of fish. When environmental managers set program goals of detecting small effect sizes (30% or less of the mean length of the target fish population) with a high statistical power (example 90%), the use of stereo-video technology

Figure 5

The effect of decreasing alpha values on the power of novice scientific divers, experienced scientific divers, and a stereo-video to detect changes in the mean length of a population of blue cod. 15% effect size; recording size = 30 fish.

in visual surveys of reef-fish length can potentially save both time and money on field costs. However, when the goal of the program is to detect larger changes, the advantages of a stereo-video system are not so great owing to the time needed to calibrate the system and analyze stereo images after the data are recorded (Harvey and Shortis, 1998).

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