

Estimating total abundance of a large temperate-reef fish using visual strip-transects

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Abstract

Total abundance estimates for the large, common, reef fish *Cheilodactylus spectabilis* (Hutton) were obtained for a marine reserve and adjacent section of coast in north-eastern New Zealand during 1985. Visual strip-transects were used to estimate abundance and size structure in both areas. The accuracy, precision and cost efficiency of five transect sizes (500, 375, 250, 100, 75 m²) were examined over three times per day (dawn, midday and dusk), by simulating transects over mapped *C. spectabilis* populations. Two transect sizes showed similarly high efficiency. The smaller of the two (20 × 5 m) was chosen for the survey because of the general advantages attributable to small sampling units. Biases related to strip-transect size are discussed. Preliminary sampling indicated that *C. spectabilis* was distributed heterogeneously, and that density was habitat-related. An optimal stratified-random design was employed in both locations, to obtain total abundance and size-structure estimates. This reduced the between-habitat source of variability in density. The total number of sampling units used was governed by the time available. The resulting total abundance estimates obtained were $18\,338 \pm 2\,886$ (95% confidence limit) for the 5 km marine reserve, compared to $3\,987 \pm 1\,117$ for an adjacent, heavily fished 4 km section of coast. When corrected for total area and habitat area sampled, this represented a 2.3-fold difference in abundance. If sampling had been designed to detect an arbitrary 10% difference in abundance within each habitat, an infeasible 440 h of sampling would have been required. Size-frequency distributions of *C. spectabilis* at the reserve had a larger model size class than distributions from the adjacent area. The data suggest that reserve status is causal in these differing abundance and size structure estimates.

Introduction

Reliable estimates of population size are important in many types of ecological study, especially those concerned with the management of exploited species. They may be of crucial importance in the study of fish populations, where management may require the imposition of quotas or protection of stocks by closing areas to fishing. An increasing literature addresses problems associated with estimating the size of reef-fish populations, and the difficulties in obtaining both accurate and precise estimates (e.g. Sale, 1980; Sale and Douglas, 1981; Sale and Sharp, 1983; Sanderson and Solonsky, 1986; Fowler, 1987; Andrew and Mapstone, in press). These problems stem from the patchy distribution of reef fishes at all spatial scales considered. This patchiness must be taken into account when designing surveys, as the usual goal of such surveys is to develop useful management policies.

It is well documented that shallow-reef systems may be divided into a number of consistent units or habitats which reflect both the physical and biological structure of the reef environment (e.g. Ebeling *et al.*, 1980; Choat and Schiel, 1982; Jones, 1984c). Studies which have examined fish distributions across reef environments have found habitat structure to have a major influence on distribution and abundance patterns (Hixon, 1980; Leum and Choat, 1980; Kingett and Choat, 1981; Jones, 1984a, b; Russ, 1985; Choat and Ayling, 1987). Fish numbers vary both within and between habitats reflecting a variety of physical and biological influences.

Typically, when habitat structure influences the abundance of fishes within a study area, a stratification technique is used to independently sample each area and identify or reduce the variation due to differences among habitats (e.g. Leum and Choat, 1980; Jones, 1984a, b; Turner and Mackay, 1985).

Stratified random sampling is the only method whereby total abundance estimates with tight confidence limits can

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be obtained for a patchily distributed species. Although stratification has been used to obtain estimates of total abundance for a variety of organisms in terrestrial environments (Siniff and Skoog, 1964; Evans *et al.*, 1966), this approach has seldom been used in marine environments. Trawl surveys have been used to determine the size of adult populations of deep-water fish (e.g. Francis, 1981). In reef environments, however, surveys have concentrated on comparisons of densities among places and times. Estimates of total abundance have not previously been obtained.

The present study applies this stratification technique to the reef environment, to obtain precise and accurate estimates of total abundance for the temperate reef fish *Cheilodactylus spectabilis* (Hutton), over two sections of coast in north-eastern New Zealand. *C. spectabilis* is a ubiquitous species on the rocky reefs of northern New Zealand (Choat and Ayling, 1987), and is the subject of high recreational fishing pressure. One section of coast examined in this study was a marine reserve in which fishing was prohibited, the other a heavily fished region. A comparison of the abundance estimates and size structures of the two populations is presented and discussed.

Visual strip-transects are employed to estimate abundance within each habitat. Although this technique has many well documented observer-biases (Ralph and Scott, 1981; Sale and Sharp, 1983), certain ecological and behavioural features make *Cheilodactylus spectabilis* amenable to visual estimation methods. *C. spectabilis* are large, conspicuous, and slow moving in habit, with approximately 30% inactive and another 40% feeding at any time of day (Leum and Choat, 1980; McCormick, 1986). Furthermore, *C. spectabilis* are neither attracted to disturbances caused by divers, nor flee from the divers' path.

Before strip-transects could be used in a stratified survey to sample the fish population, it was necessary to decide the best transect size to employ. The size of the sampling unit has been shown to greatly affect the precision and cost of an estimate (Wiebe and Holland, 1968; Wiebe, 1971; Sale and Douglas, 1981; Pringle, 1984; Downing and Anderson, 1985; Downing and Cyr, 1985; Morin, 1985). Although strip-transects are the most commonly used visual estimation technique for reef fish (Thresher and Gunn, 1986), this is one of the few studies to examine the reliability of a range of sizes to determine the optimal size for a survey.

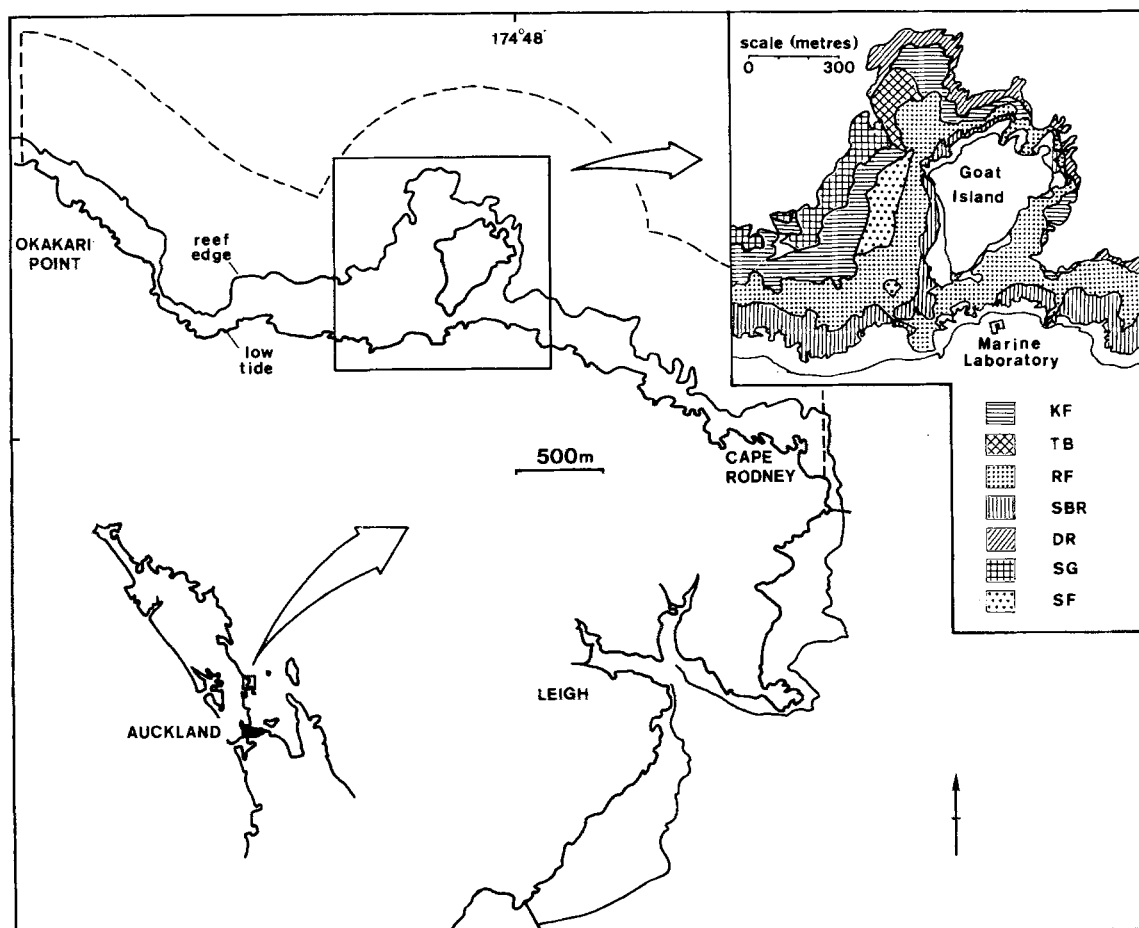


Fig. 1. Map showing location of Okakari Point to Cape Rodney Marine Reserve (boundary: dashed line), and adjacent Leigh coast (lines perpendicular to shore mark the along-shore boundary of survey area). Inset of central Reserve shows major subtidal reef habitats used as sampling strata in this study: KF, kelp forest; TB, tumble boulderbank; RF, rock flat; SBR, shallow broken rock; DR, deep reef; SG, sponge garden; SF, sediment flat

Table 1. Summary of habitat categories and identifying characteristics

Habitat	Depth (m)	Description
Rock flats	4–12	Flat or undulating. Urchin <i>Evechinus chloroticus</i> and herbivorous gastropods abundant
Kelp forests	7–22	Dense stands of the laminarian <i>Ecklonia radiata</i> ; grazing gastropods and <i>Evechinus chloroticus</i> rare
Tumble boulderbank	12–22	Large boulders forming complex tunnel and cave systems. <i>Ecklonia radiata</i> abundant on boulder tops
Shallow broken rock	1– 6	Boulders and crevices; fucoids predominate on boulder tops. Moderate densities of <i>Evechinus chloroticus</i>
Mixed rock and sand	1–15	Mixture of boulders, gravel and sand. <i>Ecklonia radiata</i> and <i>Evechinus chloroticus</i> rare
Dissected block	5–20	Massive blocks of bedrock separated by narrow canyons and gutters. Boulders at bases of blocks. <i>Ecklonia radiata</i> forms dense beds on sides and tops of blocks. On uppermost pinnacle-tops fucoids and foliose reds are common
Deep reefs	18–24	Moderately broken topography. <i>Ecklonia radiata</i> and <i>Evechinus chloroticus</i> uncommon. Sponges, ascidians and polyzoans abundant
Deep flat-reefs	22–25	Mosaic of lowlying reeflets surrounded by sand. <i>Ecklonia radiata</i> on reeflet tops, and encrusting sponges and ascidians abundant
Sponge garden	16–20	Thick sediment on rockflat with massive and finger sponges abundant
Sediment flats	5–16	Coralline turf-covered flat, trapping fine sediment. Sponges common, <i>Ecklonia radiata</i> and <i>Evechinus chloroticus</i> rare

Materials and methods

Study area

The abundance of *Cheilodactylus spectabilis* was assessed at two adjacent localities on the north-eastern coast of New Zealand during 1985. Areas surveyed were the Cape Rodney to Okakari Point Marine Reserve, and a stretch of coastline near Leigh, from Cape Rodney to Matheson Bay. The reserve covers 5 km of shallow reef environment, while the latter covers 4 km (Fig. 1). Both contain a variety of recognizable habitat types, often with discrete boundaries (Table 1). In addition, broad habitat maps of the reserve were available depicting dominant substratum coverage and reef configuration (Ayling, unpublished report; see Fig. 1: inset). No such habitat maps were available for the Leigh coast.

Optimization of strip-transects

The precision, accuracy and the cost (time) of five strip-transect sizes (50 × 10, 37.5 × 10, 25 × 10, 20 × 5, 15 × 5 m) were compared, to determine which size resulted in the most reliable estimate of *Cheilodactylus spectabilis* abundance, for the least cost. To accomplish this transect size-optimization, an area of reef 50 × 100 m was mapped in detail in the Marine Reserve. Preliminary investigations had shown this area to have intermediate densities of *C. spectabilis* (1.37 ± 0.29 (SE) per 100 m²). Ten lanes, 10 m wide and 50 m long, were marked out with nylon twine over the mapped area. Four SCUBA divers swam along the lanes, plotting on a map the position of each *C. spectabilis* seen

plus an estimate of their standard lengths. The nylon lines were laid to delimit the area to be censused by each diver, minimize recounts of individual fish and speed up the censusing process. To determine whether the estimate of transect efficiency (in terms of accuracy and precision for cost) varied over time of day, the area was censused a total of six times over two days at dawn, midday and dusk. Each census took 15 to 20 min to complete.

It was assumed that the resulting maps represented the distribution of the *Cheilodactylus spectabilis* population at the time of census. Twelve replicate transects of each size were simulated over each of the six maps. The direction of the transect (ranging 360°), and start point (coordinate) were determined using random numbers. Duplicate copies of each map were placed around the original map, to overcome the problem of transects which ran partially off the original map. All *C. spectabilis* falling within the transect area were counted. This produced a density estimate and standard deviation for each transect size and map. These were then averaged over all six maps for each transect size.

The precision (p), as reflected by the variability around the mean density estimate, was calculated for each transect size and compared. The following formula was employed (Southwood, 1966; Downing and Anderson, 1985): $p = (s/\sqrt{n})/\bar{x}$ (where s = sample standard deviation; n = number of replicates; \bar{x} = mean density).

Precision was calculated as if 3 000 m² had been sampled for each transect size. For example, for the 50 × 10 m transect, $n = 6$ since six transects are required to sample a total of 3 000 m². The replication (n) necessary for a given precision ($p = 0.075, 0.10, 0.15$) was calculated for each sample unit size by rearrangement of the terms in the above formula to: $n = (s/p \cdot \bar{x})^2$.

Accuracy was assessed by comparing the estimates of mean density obtained from the transects of various sizes to the absolute densities obtained from the mapped *Cheilodactylus spectabilis* populations.

To approximate the cost of sampling a transect, the mean time to sample each transect size was determined from triplicate transects in the field.

Stratification of survey areas

In stratified sampling, a patchily distributed population is divided up into a small number of subpopulations. The limits of the subpopulations or strata are constructed so that their average densities are as different as possible, and their variances as small as possible. With a good stratification, only a small sample is required in each stratum to obtain a confident estimate of the mean density. These can then be combined to form a precise estimate of the population total. Ideally, the division of the population into independently sampled zones is based on actual estimates of the variable under investigation; in this case the abundance of *Cheilodactylus spectabilis*. Alternatively, stratum boundaries can be defined in relation to a characteristic which is strongly related to fish density. Leum and Choat (1980) showed that a habitat classification was useful in describing the abundance patterns of *C. spectabilis*. Consequently, stratification was with respect to the various habitat types in which *C. spectabilis* occurs (Table 1).

After strata within the population have been defined, sample sizes for each stratum must be chosen, i.e., the allocation of sampling effort. There are three types of allocation: (a) simple random, in which equal numbers of sample units are taken randomly from each stratum; (b) proportional, where the number of sampling units is in proportion to the area of each stratum; or (c) optimal or Neyman, in which more sampling effort is distributed to the more variable strata. It has been found that the last alternative results in a more precise estimate of the total population, particularly when large differences exist between strata densities (Cochran, 1977). For this reason, optimal stratified random sampling was chosen to obtain total population estimates for *Cheilodactylus spectabilis*, in both the Reserve and Leigh coast surveys.

Optimum allocation of sampling units requires a knowledge of: (a) the variability in density within each stratum; and (b) an estimate of the proportion that each habitat type makes of the total reef area. A pilot study in the Marine Reserve using visual strip-transects was employed to estimate the mean density and standard deviation within each habitat. These estimates were also used in the allocation of sampling units in the Leigh survey.

For the Reserve survey, the area of each habitat type was calculated from detailed habitat maps (e.g. Fig. 1). Maps were not available for the Leigh coast however, and the proportion of each habitat was determined by swimming along transects perpendicular to the shore. Ten were placed at regular intervals along the 4 km stretch of coastline. A tape was laid out, and every 5 m the bottom type

was categorized into one of the ten habitat types defined for the Reserve survey. Transects extended from the low tide level to the edge of the reef. Preliminary investigation had found that habitat-type proportions determined by this method did not differ significantly from more intensive mapping methods (McCormick, 1986). Although error is involved in estimating stratum area, this is believed to be small. Further work may be required to minimize and account for this source of error.

A knowledge of the total reef area was necessary to scale the habitat proportions up to habitat-area estimates; this was important for the calculation of total abundance. To this end, the outer edge of the reef was delineated using the lengths of the ten transects, plus detailed depth soundings (provided by the New Zealand Hydrographic Office). The shore outline was obtained from aerial photographs of the area.

The total number of transects used in the Reserve was dictated by the time available and a maximum of three dives per day at eight 20 × 5 m transects per dive. Ten days of sampling were allotted for one pair of divers to complete the survey, yielding a total of 240 transects available for allocation to the strata. For the Leigh coast survey, the number of transects used was governed by the length of the Leigh coastline in relation to the Reserve (4.5 km), multiplied by the number of transects used in the Reserve survey, giving a total of 192 available strip-transects.

Strip-transect methodology

Thirty metres of tape were run out in a haphazard direction, under the constraint that transects should not extend outside the habitat boundaries. Transects were laid by the diver swimming 3 m above the substratum so that the fish beneath were minimally disturbed. The transect census was started 5 m into the tape and ended 5 m from the end, to counteract any displacement of fish when the ends of the tape were attached to the substratum. A distance of 2.5 m was estimated on both sides of the tape, giving a total of 100 m² sampled. Overhangs, ledges and caves were rigorously searched. In rugged areas a sinusoidal search path over the transect line was taken, so that all potential hiding places could be carefully examined.

The standard length of each fish in the transect area was recorded. *Cheilodactylus spectabilis* is ideal for visual estimates of length due to its relatively large size, conspicuous banding and slow movements. Moreover, in some cases stationary individuals could be measured *in situ*. Estimation of size prior to destructive sampling found visual estimates to be accurate to within 10%. Counts were obtained between the hours of 07.30 and 16.30 hrs, and restricted to periods of underwater visibility in excess of 6 m.

Results

Transect optimization

Time to sample a 3 000 m² area predictably decreased with increased strip-transect size, due to the added deployment

Table 2. Descriptive statistics for five transect sizes. "Estimate of sampling precision" shows number of transects required and total time taken (in parentheses) to sample these for three levels of precision, p [$p = (s/\sqrt{n})/\bar{x}$]. n : number of transects required to sample total of 3 000 m²; \bar{x} : mean density; s : sample standard-deviation. Columns (2) and (3) were calculated from six maps; Column (6) = Column (1) × Column (5); Column (7) (values in parentheses) = Column (7) (values outside parentheses) × Column (5)

Transect size (m)	n	No./sample unit area		p	Mean time ^a (min)	Sample time ^b (min)	Estimate of sampling precision for level of:		
		\bar{x}	s				0.075	0.10	0.15
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
50 × 10	6	4.74	2.81	0.242	15.4	92	62 (955)	35 (539)	16 (246)
37.5 × 10	8	3.61	2.13	0.208	13.1	105	62 (814)	35 (460)	15 (202)
25 × 10	12	2.55	2.15	0.244	8.75	105	126 (1 103)	71 (621)	32 (280)
20 × 5	30	1.01	1.07	0.193	4.00	120	200 (800)	112 (448)	50 (200)
15 × 5	40	0.96	1.44	0.278	3.40	136	402 (1 367)	226 (768)	100 (340)

^a Mean time necessary to sample each transect

^b Sample time necessary to sample 3 000 m² area

time of the small-sized transects (Table 2, Column 6). If time alone were to be considered when assessing the total abundance of *Cheilodactylus spectabilis*, then a 50 × 10 m transect would be used. With this size it took 92 min to sample the standardized area. This, however, is a comparatively small percentage saving in time, ranging from 12.3% (37.5 × 10 and 25 × 10 m) to 32.4% (15 × 5 m) (Table 2).

The accuracy of the five transect sizes at estimating the true population mean was examined. All sizes showed little difference in relative accuracy, and did not differ significantly from the true population mean (Fig. 2). However, confidence limits on the means calculated from the six mapped *C. spectabilis* distributions, indicated that the 20 × 5 m transect size is the most consistently accurate estimator of the true density.

Precision was found to have a variable relationship with transect size (Fig. 3a). Although the precision of all transect sizes was reasonably close, the most precise estimates were generated by the 20 × 5 m strip-transects, closely followed by the 37.5 × 10 m strip-transect. The former also had the lowest confidence limit around the mean precision over the pooled six-map sample. This same pattern was consistent when examined over three times of day (dawn, midday and dusk).

When the efficiency of the various transect sizes was compared, by determining the cost (in terms of total time) of obtaining a desired precision ($p=0.075, 0.1, 0.15$), a similar trend was found (Fig. 3b; see Table 2 legend for calculations). The most efficient transect size was the 20 × 5 m, once again closely followed by the 37.5 × 10 m. In contrast, the most inefficient transect was the 15 × 5 m. The percentage saving in time by using one of the former two transect sizes rather than the latter, was approximately 70% (for all precisions).

Based on the relative cost-efficiency of the five transect sizes, either the 37.5 × 10 m or the 20 × 5 m strip-transect could be legitimately used. The 20 × 5 m transect size was chosen for broad scale survey of the Reserve and Leigh coast for a number of reasons. The ease of censusing and relatively low cost allows a higher number of replicates than could be swum for the same cost using a larger tran-

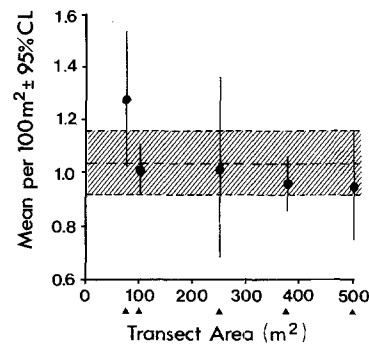


Fig. 2. *Cheilodactylus spectabilis*. Accuracy of five strip-transect sizes (arrowheads) when simulated over a mapped population. Absolute number of fish, with 95% confidence limits calculated from six maps, is indicated (shaded area)

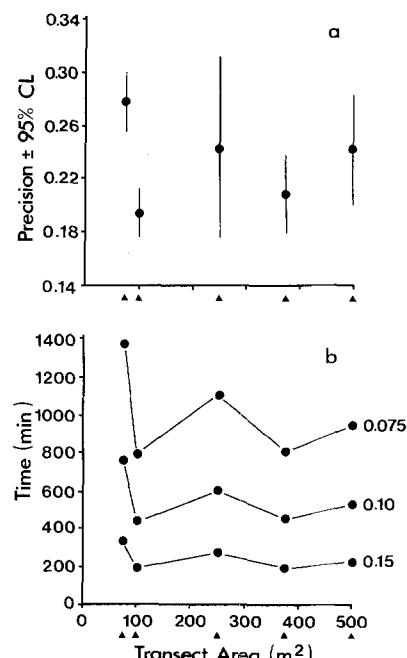


Fig. 3. *Cheilodactylus spectabilis*. (a) Relationship between precision (SE/\bar{x}) and strip-transect size (arrowheads) when assessing density over six mapped populations; (b) total sampling time required to attain three levels of precision (0.075, 0.10, 0.15), for five strip-transect sizes

Table 3. Calculation of optimal allocation of sampling units to each stratum (n_h), for Reserve and Leigh coast; allocation is based on proportional area of each habitat (W_h) plus an estimate of standard deviation of the estimated mean within each stratum (s_h); calculation of total number of transects to be allocated for Leigh survey: 4/5 km × 240 transects used in the Reserve survey = 192 (n). Absence of habitat indicated by dash. The Neyman formula, on which calculations are based, is also given. Total number of sampling units (n) used in each survey is arbitrary and was chosen on logistic constraints

Stratum	Reserve					Leigh		
	Area (m ²)	W_h	s_h	$W_h s_h$	n_h	W_h	$W_h s_h^*$	n_h
Rock flats	512 301	0.3479	1.37	0.477	85	0.333	0.456	78
Kelp forest	337 739	0.2294	1.07	0.245	44	0.293	0.314	54
Tumble boulderbank	21 127	0.0143	15.94	0.228	41	—	—	—
Shallow broken rock	296 307	0.2012	0.89	0.179	32	0.204	0.182	31
Mixed rock and sand	42 705	0.0290	2.05	0.060	11	0.043	0.088	15
Dissected blocks	52 217	0.0355	1.19	0.042	8	—	—	—
Deep reefs	54 600	0.0371	1.10	0.041	7	0.033	0.036	6
Deep flat-reefs	24 694	0.0168	2.05	0.034	6	—	—	—
Sponge gardens	69 900	0.0475	0.46	0.022	4	0.010	0.005	1
Sediment flats	60 846	0.0413	0.45	0.019	3	0.084	0.038	7
Total		1.0000		1.346	241		1.119	192

Neyman formula for optimum allocation of sampling units to strata

$$n_h = \frac{W_h \cdot s_h \cdot n}{\sum (W_h \cdot s_h)}, \text{ where } n_h = \text{optimum allocation for Stratum } h$$

* From the Reserve survey

Table 4. *Cheilodactylus spectabilis*. Arrangement of calculations to obtain population and variance estimates for Reserve and Leigh coast surveys. Definitions for Tables 4 and 5: N : total number of possible sampling units that can be fitted into the whole area; N_h : number of possible sampling units that can fit into each stratum; n : number of sampling units in the survey; W_h : proportion that each strata makes up of the total area; \bar{x}_h : mean density of fish for each stratum; s_h^2 : variance around mean density within each stratum; $s^2 (\bar{x}_{strat})$: variance of overall stratified mean density; $s (\bar{x}_{strat})$: standard deviation of overall stratified mean density (i.e., standard error)

Strata	Area (m ²)	% Area	N_h	W_h	n_h	\bar{x}_h	s_h^2	$\frac{W_h^2 s_h^2}{n_h}$	$N_h \bar{x}_h$	% Fish
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Reserve survey										
Rock flats	512 301	35	5 123.0	0.3479	85	0.607	1.219	1.74×10^{-3}	3 109.67	17
Kelp forest	337 739	23	3 377.4	0.2294	44	0.929	1.092	1.31×10^{-3}	3 137.60	17
Tumble boulderbank	21 127	1	211.3	0.0143	41	15.867	223.223	1.11×10^{-3}	3 352.22	18
Shallow broken rock	296 307	20	2 963.1	0.2012	32	2.091	4.023	5.09×10^{-3}	6 195.78	34
Mixed rock and sand	42 705	3	427.1	0.0290	11	0.364	0.455	3.48×10^{-5}	155.45	1
Dissected blocks	52 217	4	522.2	0.0355	8	1.500	3.143	4.95×10^{-4}	783.26	4
Deep reefs	54 600	4	546.0	0.0371	7	1.714	2.238	4.40×10^{-4}	935.88	5
Deep flat-reefs	24 694	2	246.9	0.0168	6	2.000	1.600	7.53×10^{-5}	493.88	3
Sponge gardens	69 900	5	699.0	0.0475	4	0.250	0.250	1.41×10^{-4}	174.75	1
Sediment flats	60 846	4	608.5	0.0413	3	0	0	0	0	0
Totals	1 472 436		14 724.4	1.0000	241			0.010	18 338	
Leigh survey										
Rock flats		33	3 093.2	0.333	78	0.231	0.440	6.14×10^{-4}	714.53	18
Kelp forest		29	2 746.4	0.293	54	0.371	0.464	7.38×10^{-4}	1 018.91	26
Shallow broken rock		21	1 912.2	0.204	31	0.839	1.540	2.07×10^{-3}	1 604.30	40
Mixed rock and sand		4	403.1	0.043	15	0.467	0.410	5.05×10^{-5}	188.23	5
Deep reefs		3	309.3	0.033	6	1.500	1.900	2.85×10^{-4}	461.14	12
Sponge gardens		1	121.9	0.013	1	0	0	—	—	0
Sediment flats		9	787.4	0.084	7	0	0	—	—	0
Totals			9 373.3	1.000	192			3.76×10^{-3}	3 987	

sect. Large sample numbers increase the robustness of most statistical analyses in the face of violations of assumptions (Green, 1979; p. 39). Moreover, small transects allow the easy assessment of one habitat type, rather than traversing a range of habitats, and by doing so inflating the estimated sample variance. In addition, observer fatigue may increase bias and decrease precision when large numbers of organisms are being counted (Caughley, 1977; Green, 1979). Consequently, it is likely that small transects will be searched more thoroughly than large transects (Andrew and Mapstone, in press).

Density and distribution

Preliminary sampling enabled the optimal allocation of sampling units in the main surveys by Neyman allocation (see Table 3). Stratification by habitat type, and randomly allocating 20 × 5 m strip-transects within each habitat resulted in a precise density estimate of *Cheilodactylus spectabilis* over both reef areas. A total of 851 *C. spectabilis* were recorded within transects in the Reserve (5 km coast and 147 ha reef). This value was expanded to 18 338 with 95% confidence limits of 2 886, by use of computations shown in Table 4 and summarized in Table 5 (formula from Cochran, 1977). In contrast, a total of only 80 fish were counted during the survey of the Leigh coast (4 km coast and 94 ha reef). This was expanded to a population estimate of 3 987, with 95% confidence limits of 1 117. When corrected for differences in the total reef area and the contribution of each habitat type sampled, the Reserve has 2.3 times as many *C. spectabilis* than coastal Leigh.

A two-factor analysis of variance tested for differences in the densities of *Cheilodactylus spectabilis* between two survey areas, over the three main habitat types (i.e., kelp forests, rock flats and shallow broken rock) (Table 6). All eight habitats in common could not be used due to inadequate replication. Because of unequal sampling in each habitat, samples were balanced by the random removal of transects prior to analysis. The non-significant interaction term suggests that there was a consistent difference in density among the three habitat types, even though density was markedly different between the two locations. Both main factors of location and habitat were predictably significant. A Tukey's HSD test indicated that densities of *C. spectabilis* in kelp forests and rock flats differed significantly from those in shallow broken-rock habitats. By far the largest proportion of the total variation was explained by differences between replicate transects within a habitat (69.1%). Moreover, the proportion explained by the differences in density between habitats (13.9%) was as high as that between the Reserve and Leigh (14.7%).

A summary of the distribution of *Cheilodactylus spectabilis* by habitat area is given in Table 4 (Columns 2 and 10). This illustrates the distinct difference in densities of *C. spectabilis* by habitat, picked up by the previous analysis. Eighteen percent of the fish occurred in the tumble boulderbank habitat, which comprised only 1% of the total area of reef in the Reserve. Similarly, 34% of individuals oc-

curred in the shallow broken rock, which made up 20% of the area. Overall, 52% of the fish occurred in these two habitats. No analysis of the between-habitat density differences was carried out on the Leigh survey due to the low numbers present in each habitat.

Table 5. *Cheilodactylus spectabilis*. Summary of population and variance estimates for Reserve and Leigh surveys. Terms defined in Table 4

Estimate	Location	
	Reserve	Leigh
Population estimate $X = \sum \bar{x}_h \cdot N_h$	18 338	3 987
Variance of stratified mean $s^2(\bar{x}_{strat}) = \sum \frac{W_h^2 \cdot s_h^2}{n_h}$	0.01	0.0037
95% confidence limits $X \pm t_{0.05} \cdot N \cdot s(\bar{x}_{strat})$	2 886	1 117

Table 6. *Cheilodactylus spectabilis*. Two-factor ANOVA comparing densities in the Reserve and Leigh coast over three habitats. Percentage of total variation explained by each term is given. (Transformation: square root; $n = 31$; *** significant at 0.001 level)

Source of variation	DF	MS	F	P	%
Location	1	8.186	20.72	***	14.7
Habitat	2	5.335	13.51	***	13.9
Location × habitat	2	0.804	2.04	NS	2.3
Residual	180	0.395			69.1

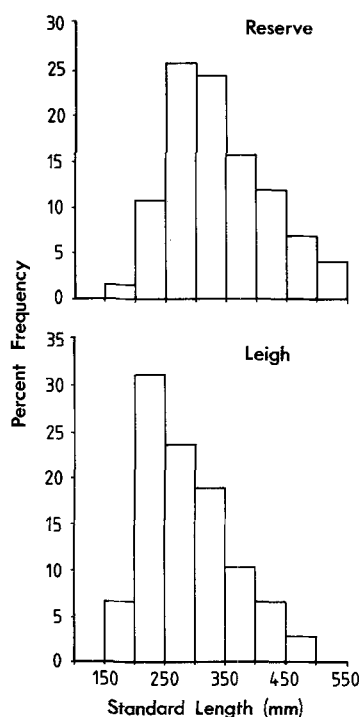


Fig. 4. *Cheilodactylus spectabilis*. Size-frequency distributions over Marine Reserve, and Leigh coast

A comparison of the size distributions of *Cheilodactylus spectabilis* in the two areas indicated that the Leigh population was skewed toward the smaller size classes compared to that of the Reserve (Fig. 4). Few individuals were larger than 500 mm SL, and only 38% were larger than 300 mm SL compared to 62% in the Reserve population.

Discussion

This exercise using *Cheilodactylus spectabilis* demonstrates that it is possible to optimize strip-transect size, in terms of accuracy and precision, when a single target-species is involved. The optimal transect size which results is likely to be species-specific. Accordingly, a compromise in transect size would be required if several species were to be counted within the same transect.

The transect-simulation method used in this study to optimize transect size was based on the assumption that the relative reliability of simulated transects reflected that of field transects. Reliability is determined by two sources of variation present in all sample data: (a) variation in the arrangement of organisms in the real world, which the sample attempts to estimate; (b) variation due to biases associated with the sampling methodology, i.e., error. The first of these sources is governed by the size of the sampling unit relative to the scale at which members of the population aggregate. A transect smaller or equal to the scale of clumping will give more variable estimates than a transect which is larger than the scale of clumping (Wiebe, 1971; Green, 1979). An excessively small transect size will result in a large number of transects containing no individuals, plus a few with many (as patches are sampled). On the other hand, a too large transect size may confound density estimation by incorporating a higher level of variation (e.g. the between-habitat source). In the mapping method, this aspect of sample variation was minimized. Since transects were simulated, sizes were compared devoid of sampling error.

The biases of the strip-transect method which result in this sampling error, however, can be important contributors to the magnitude of the final estimate of variance for the sample data (McDonald, 1981). These biases have been well known and extensively documented by terrestrial ecologists for many years (Southwood, 1966; Emlen, 1971, 1977; Caughley, 1974, 1977; Robinette *et al.*, 1974; Ralph and Scott, 1981). They have only recently drawn attention from marine ecologists (Sanderson and Solonsky, 1980, 1986; Brock, 1982; Sale and Sharp, 1983; Fowler, 1987). Biases stem from three broad sources, all of which interact to compound errors in estimation:

(a) Observer variability – for example, the experience of the observer to lay the transect tape with minimal disturbance to the survey population, and to rapidly identify species or sex stages. An important consideration here is the “edge-effect” associated with the transect size, i.e., consistently including individuals that ought to be excluded or *vice versa*.

(b) Fish characteristics – for example, the crypticity of the fish, with varying conspicuousness of differing sex-stages and size classes. The reaction of the target fish to the observer leading to recounts or missed fish is the major determinant of whether this technique can be used to assess densities of a species.

(c) Environmental factors – for example, turbidity, topographical complexity and floral characteristics of the surveyed area which affect the visibility of the target species.

Little work has been done on quantifying the effect of these biases on the accuracy or precision of the abundance estimate. An exception is the work of Sale and Sharp (1983), who examined the effect of transect width on density estimates of five species groups of fish in a heterogeneous coral reef system. They identified strip width as an important source of bias leading to the substantial underestimation of density, and found the magnitude of underestimation increased with increased strip transect width. For demersal fish, rigorous searching of the strip transect may reduce this problem, especially for narrow transects. Obviously more work on the biases inherent in strip-transects is required.

Because the mapping method compares the reliability of various strip sizes without accounting for these sources of sampling error, biases such as strip width and edge effects which are known to be of major importance (Grieg-Smith, 1983; Sale and Sharp, 1983) were considered in choosing the optimal size used in the survey. Training of personnel and standardization of methodology, at least within a particular survey, can reduce or remove many of the biases which can potentially affect the reliability of an estimate.

This study emphasizes the gains to be obtained through an investigation of sample unit efficiency prior to the initiation of a large sampling programme. There was a 70% saving in time using a 20×5 m rather than the slightly smaller 15×5 m transect to obtain a given level of precision. This is not a unique finding with similar conclusions being reached for a wide range of taxa (Pringle, 1984; Downing and Anderson, 1985; Downing and Cyr, 1985; Morin, 1985; Heisey and Hoenig, 1986).

The objective of the present study was to obtain a precise estimate of total abundance for *Cheilodactylus spectabilis* in the Reserve and adjacent area of coast, for a predetermined cost in time. Thus it was the total effort available, rather than set levels of precision, which governed how many transects would be used, and the resulting confidence of the abundance estimate. In many instances, however, there is a compromise between cost (in time or money), and a precision set by the researcher (e.g. $p = 0.05$, 0.10, etc.). This situation often arises in surveys to assess the abundance or standing crop of a commercial species to determine quotas, where funding is often limited and a certain minimal level of precision is required for the information to be useful. In this instance, since each stratum can be treated as a single sample, the replication needed to obtain a desired precision can be calculated for each stratum sep-

arately, by the rearrangement of the general formula for precision (as in "Materials and methods"). If this total effort is beyond the limits of the survey, then the precision should be relaxed, or the question redefined.

Often, due to the limitations of finance, however, a survey is required to both estimate abundance and allow formal comparisons between areas or through time. In this case, the simplest design is a stratified simple random sample, whereby equal numbers of replicates are allocated to the sampled strata. Under most circumstances this design would result in a less precise estimate of total abundance than would be obtained if optimal or proportional stratification was used (Cochran, 1977). However, the unbalanced replication of such designs are not well suited to statistical comparisons (Andrew and Mapstone, in press). The total abundance estimate can be calculated in the same way as was done in this study for optimum stratification (formulae in Cochran, 1953).

This study illustrates the advantages of stratifying by habitat type for a reef fish survey. The precision gained by using stratified random sampling instead of the typically used simple random sampling can be seen by a comparison of the variances obtained from each sampling method. Cochran (1953) provides a formula for estimating the variance for simple random sampling from stratified random data. The variance for simple random sampling is estimated to be $s^2(\bar{x})_{\text{ran}} = 0.03$ (variance of the sample mean) for the Reserve; three times higher than the variance obtained from stratified sampling of $s^2(\bar{x})_{\text{strat}} = 0.01$. The Leigh survey exemplifies this with an almost 200-fold decrease in the variance associated with the density estimate by stratification. Clearly, stratification, by reducing the error component associated with between-habitat variation in abundance, has greatly increased precision.

The high variability in density identified at the replicate level (69% of total) within a habitat, suggests that further division of the habitats into independently sampled strata would improve precision. Leum and Choat (1980) found a strong positive relationship between the topographic complexity or "rugosity" (*sensu* Luckhurst and Luckhurst, 1978) of the reef areas and densities of *Cheilodactylus spectabilis* ($r^2 = 0.77$). Furthermore, Choat and Bellwood (1985) detected differences in abundance and species composition of herbivorous fishes at Lizard Island on the Great Barrier Reef, and associated these with small but measurable differences in reef structure. Stratification of a reef by such easily measured environmental and floral characteristics, rather than a gross habitat delimitation, will markedly improve the precision of the abundance estimate. This will only be achieved however, by a substantial increase in effort.

Whether this extra effort is worthwhile will depend on the reason for which the survey was designed. If a population of fish in a given area is being monitored to measure the impact of fishing, then a high degree of precision can be prohibitively time-consuming and unwarranted. For example, to obtain the precision required to detect an arbitrary 10% change in the *Cheilodactylus spectabilis* popu-

lation in the Reserve (i.e., have a 95% confidence limit 10% either side of the mean), a total of 6 610 samples are required. This is an unfeasible number of samples, involving some 441 h of transect sampling alone. In this study, a confidence limit 16% either side of the estimate was attained for *C. spectabilis* in the Reserve. The confidence limit for the Leigh survey was somewhat larger due to the comparatively low numbers encountered. This was more than sufficient to illustrate the three-fold difference in abundance between the two areas.

Of possibly greater value than a highly precise abundance estimate, is a knowledge of the size-frequency distribution of the population. Size structure of a fish population, when linked with an even rudimentary knowledge of the biology of the species, can allow suggestions regarding recruitment to the adult population, fishing intensity and rates of recovery from fishing. The size-frequency distribution of *Cheilodactylus spectabilis* in the Reserve was found to have a larger modal size class than the distribution from the non-reserve area. Given the vulnerability of *C. spectabilis* to spear and gill-net fishing, this difference in size structure is suggestive of a fishing effect.

This study provides an example of how sample-unit optimization can be combined with stratification, to produce an economical and precise estimate of total abundance for a shallow temperate-reef fish. Furthermore, it provides the basis for a future comparison of population structure and abundance of *Cheilodactylus spectabilis* between the two areas.

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