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Monitoring Benthic Algal Communities: A Comparison of Targeted and Coefficient Sampling Methods

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Choosing an appropriate sample unit is a fundamental decision in the design of ecological studies. While numerous methods have been developed to estimate organism abundance, they differ in cost, accuracy and precision. Using both field data and computer simulation modeling, we evaluated the costs and benefits associated with two methods commonly used to sample benthic organisms in temperate kelp forests. One of these methods, the Targeted Sampling method, relies on different sample units, each "targeted" for a specific species or group of species while the other method relies on coefficients that represent ranges of bottom cover obtained from visual estimates within standardized sample units. Both the field data and the computer simulations suggest that both methods yield remarkably similar estimates of organism abundance and among-site variability, although the Coefficient method slightly underestimates variability among sample units when abundances are low. In contrast, the two methods differ considerably in the effort needed to sample these communities; the Targeted Sampling requires more time and twice the personnel to complete. We conclude that the Coefficient Sampling method may be better for environmental monitoring programs where changes in mean abundance are of central concern and resources are limiting, but that the Targeted sampling methods may be better for ecological studies where quantitative relationships among species and small-scale variability in abundance are of central concern.

Key Words: benthic organisms, environmental monitoring, kelp forest, point contacts, sampling design

INTRODUCTION

Ecological studies rely on quantitative sampling techniques to estimate patterns of organism distribution and abundance. In the case of benthic marine algae, some sampling designs allow researchers to collect samples in the field and examine them in the laboratory, often termed "destructive sampling," while many other sampling designs require that the sampling be non-destructive and entirely *in situ*. Numerous methods have been developed for this task and a growing list of review papers and texts have compared their abilities to correctly estimate organism abundance (e.g. Foster 1985; Littler and Littler 1985; Foster *et al.* 1991; Meese and Tomich 1992; Dethier *et al.* 1993; Leonard and Clark 1993; Cabral and Murta 2004). Questions concerning the accuracy (ability to estimate the true mean), precision (ability to produce similar estimates upon repeated sampling), statistical power (ability to detect differences between sample groups or dates) and cost (both monetary and time required to sample) of different sampling techniques are of particular importance to ecologists, especially those working in subtidal and intertidal habitats where sampling time is limited by logistic and physiological constraints. Consequently, choosing a sampling design that provides the greatest accuracy, precision, and power while minimizing cost is of fundamental importance, especially for studies that plan to continue sampling into the future and where the ability to detect change is of central concern.

A review of scientific papers and texts on sampling design indicates that estimates of organism density for larger non-colonial benthic species are relatively straightforward to make; simply count the number of individuals in standardized units of area (e.g. quadrats or swaths) and upon repeated unbiased sampling of these units, determine the mean and variance of the estimate. While this approach may work quite well when unique individuals can easily be identified and counted *in situ*, it

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may not be appropriate for species whose individuals are not easily discriminated from one another but are better described by the amount of substrate they cover. For these organisms, methods that estimate percent bottom cover have been developed that rely on photographic records (e.g. Connell 1970; Littler 1971), visual estimates (e.g. Dethier *et al.* 1993; Edwards 1998), and point contacts/intercepts (e.g. Cowen *et al.* 1982; Clark *et al.* 2004). In general, photographic records require the least amount time to collect in the field but they tend to require considerable time to analyze in the laboratory, preclude sampling species that occur in layers, and often reduce the ability to resolve species with similar morphologies (Foster *et al.* 1991; Leonard and Clark 1993). *In situ* visual estimates of bottom cover improve the ability to resolve species with similar morphologies and provide additional information for species that occur in layers, but this approach may introduce experimenter bias and therefore not be as accurate or precise as photographic methods (Dethier *et al.* 1993). Point contact methods provide unbiased quantitative estimates of bottom cover but they are the most time consuming in the field and have the tendency to miss rare species (Cowen *et al.* 1982; Dethier *et al.* 1993; Clark *et al.* 2004).

Many of the problems encountered in the point contact method of sampling were ameliorated by Braun-Blanquet and Pavillard (1922) who developed a method for assessing percent bottom cover of benthic species that reduces sampling time as well as the likelihood of missing rare species. Their method also relies on *in situ* visual estimates of cover within standardized units of area (e.g. quadrats), but does so by categorizing ranges of cover into discrete bins (e.g. 5 to 15%) and assigning coefficients to represent those bins, thus reducing experimenter bias. Modifications to this technique include the application of coefficients to other biologically relevant metrics, such as organism volume (e.g. Boudouresque 1971) and biomass (e.g. Boudouresque 1969). Benefits to the Coefficient method are that it is relatively quick, inexpensive, and when used by an experienced researcher, consistently repeatable. Problems with this approach, however, are that it is thought to overestimate organism abundance in some cases, although the degree to which this occurs is probably negligible (Boudouresque 1971), and it may not produce accurate quantitative estimates of bottom cover. To address this latter concern, Boudouresque (1971) developed a method for quantitatively analyzing coefficient-based data in which each coefficient is considered to represent the median of its range of percent-cover values, and upon repeated sampling the coefficients are transformed to these median values. Like Braun-Blanquet and Pavillard, Boudouresque presented six categories; "1" to indicate a species exhibited between 0 and 5% bottom cover (median = 2.5%), "2" to indicate a species exhibited between 6-25% (median = 15%), "3" to indicate a species exhibited between 26-50% (median = 37.5%), "4" to indicate a species exhibited between 51-75% (median = 62.5%), "5" to indicate a species exhibited between 76-95% = (median = 85%), and "6" to indicate a species exhibited between 96-100% (median = 97.5%). Because this method does not require detailed counting or measuring, it can be done quickly and inexpensively. Also, because these estimates are often made within quadrats, the number of unique individuals of other species can be counted simultaneously, thereby yielding estimates of organism density as well as bottom cover with little added cost. Consequently, numerous ecological studies and environmental monitoring programs have adopted this or similar coefficient-based sampling designs to track changes in organism abundance and distribution (e.g. Widdowson 1971; Lindstrom and Foreman 1978; Thom and Widdowson 1978; Carter and VanBlaricom 1998; Estes *et al.* 1998).

Given sufficient resources and time, researchers may choose to estimate the abundance of different classes of organisms using a variety of sampling methods. For example, percent bottom cover of encrusting or turf species may be estimated using point contacts, density of small or relatively common organisms may be estimated within quadrats, and density of large or rare organisms may be estimated along transects or swaths. Such an approach (hereafter Targeted Sampling) may be especially beneficial if the size of each sample unit is selected on the basis of biologically relevant criteria (e.g. accounting for the size and/or abundance of the target species). While Targeted Sampling may provide the best estimates of organism abundance, it does so at the greatest cost in terms of time and effort required to sample. However, while the costs of Targeted Sampling are easy to measure, the extent to which this method more accurately estimates bottom cover and/or density of benthic organisms relative to other sample methods is uncertain. In this paper, we compare how well these two sampling methods, Coefficient and Targeted, estimate density and bottom cover of benthic organisms and assess their abilities to detect changes in these estimates over time.

MATERIALS AND METHODS

Field surveys

Study sites: The field portion of this study was done over a three-year period (1998-2001) at five locations that spanned ~500 km along the Pacific coast of Baja California, México (Figure 1). Within each location, three 8-12 m deep rocky reef sites were randomly selected and surveyed for algal and invertebrate abundance. These sites supported a diverse community consisting of canopy-forming kelps, a rich mosaic of understory and turf algae, and numerous species of encrusting invertebrates. Field surveys were done in June 1998, October 1998, June 1999, October 1999, and June 2000, a period following one of the strongest El Niño Southern Oscillation events ever recorded (Wolter and Timlin 1998; Edwards 2004).

Targeted Sampling: We estimated the density and bottom cover of six common kelp forest species and/or groups of species at each site on each sampling date during the three-year period. Species groups were defined by broad taxonomic affiliation (e.g. red vs. brown algae) and general similarities in morphology (e.g. fleshy vs. encrusting vs. geniculate algae; *sensu* Littler and Littler 1980). At each site, a single researcher using SCUBA estimated the abundance of all adult (> 1 m tall) giant kelp, *Macrocystis pyrifera* (Agardh) (hereafter *Macrocystis*), along three randomly directed 20 m × 2 m transects. Along each transect, the same diver also counted all adult individuals of the subsurface stipitate kelp, *Eisenia arborea* (Areschoug) (hereafter *Eisenia*), and kelp recruits (all local species in the order Laminariales) within five 1 m^2 quadrats (n = 15 per site). A second researcher estimated the percent bottom cover of fleshy red algae, geniculate coralline algae, and sessile invertebrates at five randomly selected positions along each transect (n = 15 per site) using Random Point Contacts (RPCs). Here, five knots were tied on a loose string that was attached at both ends to a one meter long bar. The string was pulled taut, the knot pressed to the substrate, and the organism in contact with the knot identified at each of the five knot points. The string was then moved to the other side of the bar and five additional points were sampled (n = 10 points per RPC position). All estimates of density and bottom cover for a site could be obtained by two researchers on a single 40-50 min dive. Although variability in estimated organism abundance among researchers generally accounted for < 5% of the total variance in organism abundance using these sample methods (see Edwards 2004), we randomized task allocation among researchers before each sample event to minimize potential consistent bias in these estimates.

Coefficient Sampling: All Coefficient method data were obtained within 0.5 m^2 quadrats. This quadrate size was chosen because it is a size commonly used in ecological studies and is the largest quadrat size within which our researchers could confidently visually estimate bottom coverage of all targeted organisms. We conducted the Coefficient sampling concurrently with the Targeted sampling, such that a second set of researchers sampled the same sites on the same dates described above for the Targeted Sampling method. We used the Coefficient method to estimate the abundance and bottom cover of the same six common kelp forest species and/or functional groups described above simultaneously in the same quadrat. In contrast with the Targeted Sampling method, a single diver was able to make all measures of density and bottom cover during a single 20-40 min dive, which freed up the second diver to collect samples for laboratory analyses, exchange oceanographic instruments, or conduct other tasks. Quantitative estimates of percent bottom cover were then made using the coefficient median points described above (see Boudouresque 1971).

Field data analyses

Estimates of abundance and bottom cover were compared between the two sample methods and among the five sample dates for each species and/or group both graphically and using separate two-way mixed-model ANOVAs, with sample Date as a random factor and sample Method as a fixed factor. Examination of the Method x Date interactions identified cases where the two methods differed in their estimates of density and bottom cover of a particular species over time. This occurred only once, for juvenile kelps (see Results). To examine this further, Fisher's LSD pair wise comparisons were conducted on the Date x Method interaction. Prior to testing, all data were examined for homogeneity of variances using Cochran's C test and for normality by graphical examination of the residuals. Data failing to meet these assumptions were square root transformed and retested to ensure that any problems were corrected.

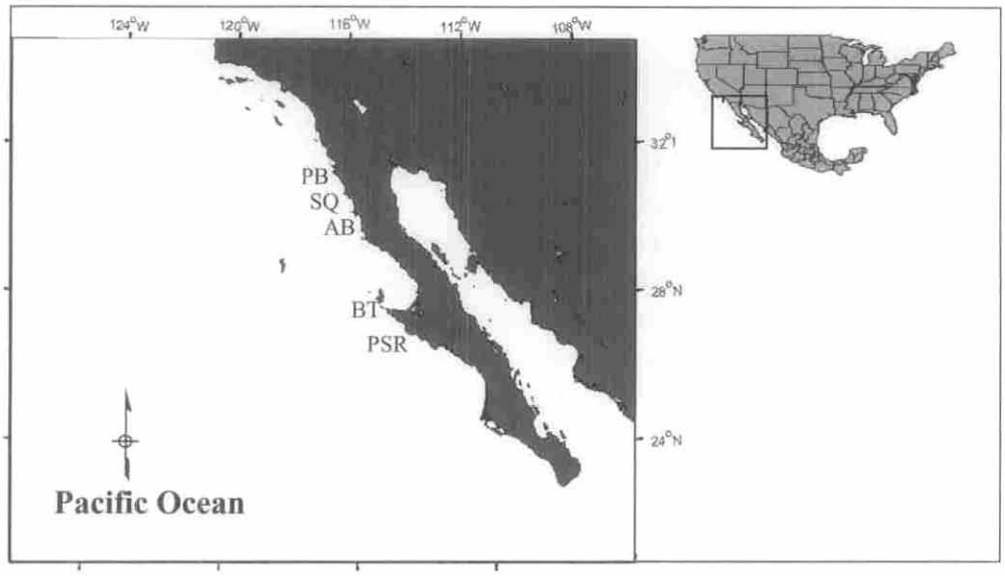

Fig. 1. Map showing the five study locations along the west coast of California, USA and Baja California, México.

Computer simulation model

We developed a program to simulate 27 alternate scenarios of abundance and distribution of a hypothetical target species using the computer program Matlab© (MathWorks, Inc., Natick, MA). These 27 scenarios corresponded to orthogonal combinations of low, medium and high levels of three statistics: 1) mean percent bottom cover, 2) within-site variability in abundance, and 3) among-site variability in abundance. All levels of these three statistics were set within the range of values reported in published data sets for benthic species (Edwards 2001). Specifically, the three levels of mean percent bottom cover chosen for this exercise were 10%, 30%, and 70% (hereafter L, M, H respectively), and the three levels of within-site variation in bottom cover (expressed as CV's) were set to σ^2 = 5%, 10% and 20%. The three levels of among-site variation in bottom cover corresponded to specific combinations of site means (we allowed for 3 separate sites in our simulation model), with one of three possible combinations of site means (chosen at random) for each level of among-site variation:

Low = H H H *or* M M M *or* L L L
Medium = L M M *or* H H M *or* M L L
High = H M L *or* H H L *or* H L L

We then simulated the sampling of these 27 alternative populations (over 1000 replications) using both Random Point Contacts (hereafter RPC) and the Coefficient method, and graphically compared the resulting estimates of bottom cover. Specifically, at each replication of the simulation model and for each of the 27 scenarios, we generated percent cover values for each sample within each site by drawing randomly from Beta distributions, with the Beta parameters adjusted to produce (asymptotically) the statistic values listed above. Sample sizes for the simulations corresponded to those used in the field sampling portion of this study. To compare the two sampling methods' ability to accurately estimate bottom cover, we plotted average deviations (± 95% CI) between the means of our sample estimates (as derived from model) and the true means (known from model parameterization), for each level of bottom cover. To examine the precision of each sample method, we plotted the average within-site coefficient of variation (± 95% CI) for each level of bottom cover, and plotted average among-site CV (± 95% CI) for each level of among-site variation.

RESULTS

Field survey results

Estimates of density and bottom cover: The Targeted Sampling and the Coefficient methods did not differ significantly in their estimates of density and/or bottom cover for any of the six species or functional groups, or in their ability to detect changes in density and/or bottom cover over the three-year study (Table 1; Figs 2 & 3). Specifically, both methods did detect significant changes in the mean density of *Macrocystis* and juvenile kelps, and in the mean bottom cover of sessile invertebrates over the three-year study, but neither method detected changes in the mean density of *Eisenia* or the bottom

Table 1. Results of two-way mixed model ANOVAs (Date = random and Method = fixed) testing variation in the density and bottom cover estimates over the three-year study using Coefficient and Targeted sampling techniques. Bold-face values are significant ($p < 0.05$)

Species/group	Source	SOS	df	MS	F-ratio	*P*-value
Macrocystis pyrifera	Date	0.29	4	0.07	6.27	**0.01**
	Method	0.01	1	0.01	0.71	0.45
	D x M	0.01	4	0.01	0.61	0.65
	Error	1.19	100	0.02		
Eisenia arborea	Date	6.40	4	1.60	1.54	0.19
	Method	0.52	1	0.52	0.27	0.63
	D x M	1.92	4	1.85	0.61	0.13
	Error	103.851	100	1.04		
Juvenile kelps	Date	214.20	4	53.33	3.64	**0.01**
	Method	100.10	1	100.10	2.06	0.22
	D x M	194.14	4	48.53	3.29	**0.01**
	Error	1471.22	100	14.71		
Geniculate Coralline Algae	Date	1383.18	4	345.79	1.10	0.36
	Method	143.43	1	143.43	0.41	0.56
	D x M	1401.70	4	350.43	1.12	0.35
	Error	1.19	100	0.02		
Fleshy Red Algae	Date	1821.76	4	455.44	1.23	0.30
	Method	10.83	1	10.83	0.04	0.85
	D x M	960.91	4	240.23	0.65	0.63
	Error	1.19	100	0.02		
Sessile Invertebrates	Date	8556.19	4	2139.05	7.65	**0.01**
	Method	554.05	1	554.05	3.57	0.13
	D x M	620.81	4	155.20	0.55	0.69
	Error	1.19	100	0.02		

cover of either fleshy red or geniculate coralline algae during this period (Table 1; Figs 2 & 3). The sole exception for this occurred for juvenile kelps (Date x Method interaction, $p < 0.01$). Here, the two methods did not differ in their estimates of density on the first (June 1998), second (October 1998) fourth (October 1999) or fifth (June 2000) sample dates (Fishers LSD, $p = 0.17$, 0.95, 0.95, 0.88 respectively), but the Coefficient method produced higher estimates of density on the third (June 1999) sample date (Fishers LSD, $p < 0.01$). Starting densities for adult kelps were low due to mortality that occurred prior to the study during the strong 1997-1998 El Niño Southern Oscillation (Edwards 2004).

Computer simulation results

Computer-simulated sampling of the 27 alternative scenarios representing orthogonal combinations of low-medium-high levels of percent bottom cover, within-site variability and among-site variability yielded results that were generally consistent with the field survey data. The computer models indicated that repeated sampling of these populations using simulated RPCs accurately estimated the true (parameterized) population mean regardless of how abundant or variable the simulated target species was (Fig. 4A). Sampling of these populations using simulated coefficients was only slightly less accurate, and tended to slightly overestimate bottom cover (by $\leq 4\%$) when cover was medium (30%) to low (10%), and underestimate bottom cover (by $\leq 4\%$) when cover was high (70%). These over- and underestimates were only significant (i.e. the true mean fell outside the 95% confidence interval about the sample mean) when within-site variability was low. The two methods did not differ substantially in their estimates of variability, although sampling of populations with low bottom cover was slightly less precise using RPCs (Fig. 4B) likely because the coefficient method ignores variability within each category and only relies on the mean for that category. Further, both methods tended to be more precise when mean bottom cover was medium to high, although

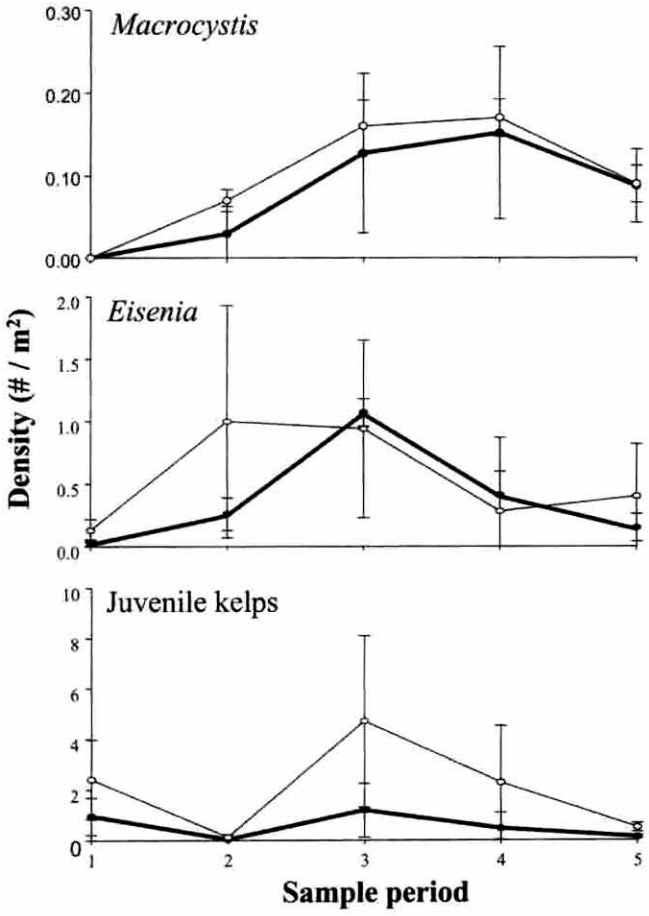

Fig. 2. Mean density (± 1 se) of *Macrocystis*, *Eisenia*, and juvenile kelps for the five study locations over the three-year period as determined with the Targeted Sampling (thick dark lines, shaded circles) and Coefficient (thin light lines, open squares).

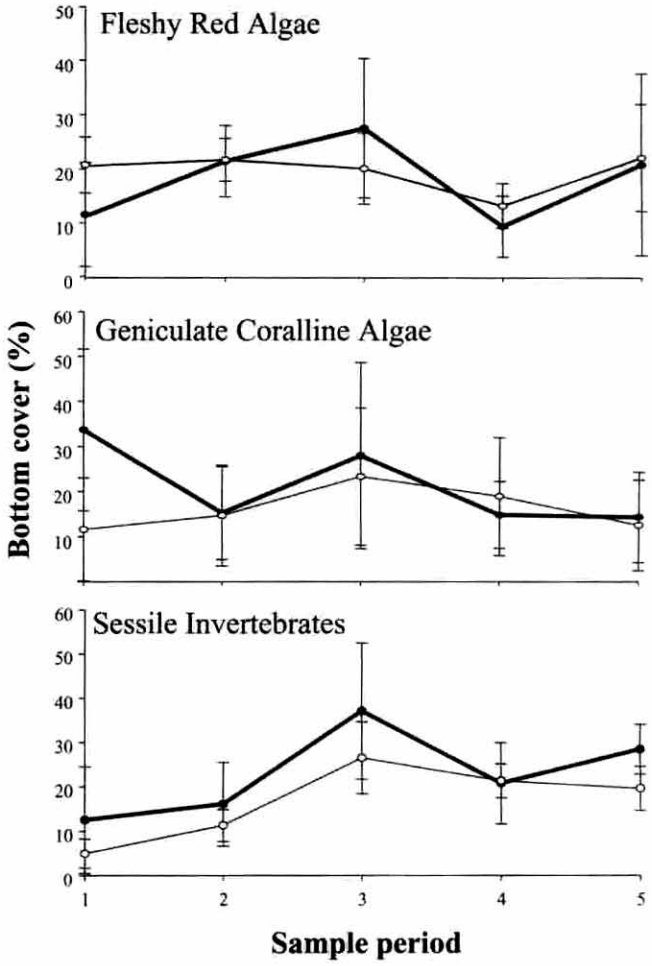

Fig. 3. Mean bottom cover (± 1 se) of Fleshy Red algae, geniculate coralline algae, and sessile invertebrates for the five study locations over the three-year period as determined with the Targeted Sampling (thick dark lines, shaded circles) and Coefficient (thin light lines, open squares).

this was likely an artifact of placing a larger number in the denominator when calculating the coefficient of variation. Finally, although the random point contact method tended to yield slightly higher estimates of among-site variability in all populations regardless of how they were parameterized, estimates of variability among sites did not differ significantly between the two methods regardless of within-site or among-site variability (Fig. 4C). Altogether, while the coefficient method may slightly overestimate bottom cover when cover is low to medium (see also Boudouresque 1971) and underestimate bottom cover when cover is high, the simulation model results generally support the results of the field comparisons, in that the two methods do not differ greatly in their ability to estimate mean bottom cover.

DISCUSSION

Researchers and environmental resource managers designing ecological studies and environmental monitoring programs have long realized the need to optimize field sampling protocols in order to minimize the time and resources needed to sample (cost) while increasing the accuracy of their estimates of organism abundance (benefit). These considerations may be especially important to environmental monitoring programs aimed at chronicling changes in intertidal and subtidal benthic marine ecosystems where the added costs of research vessels, the physiological constraints imposed on SCUBA divers, and the limited time available during low tides can be limiting factors. We evaluated the costs and benefits associated with two methods commonly used to sample benthic organisms in temperate kelp forests to determine if they differed in their abilities to accurately estimate abundances and bottom covers of the most conspicuous kelp forest species over a three-year period. We

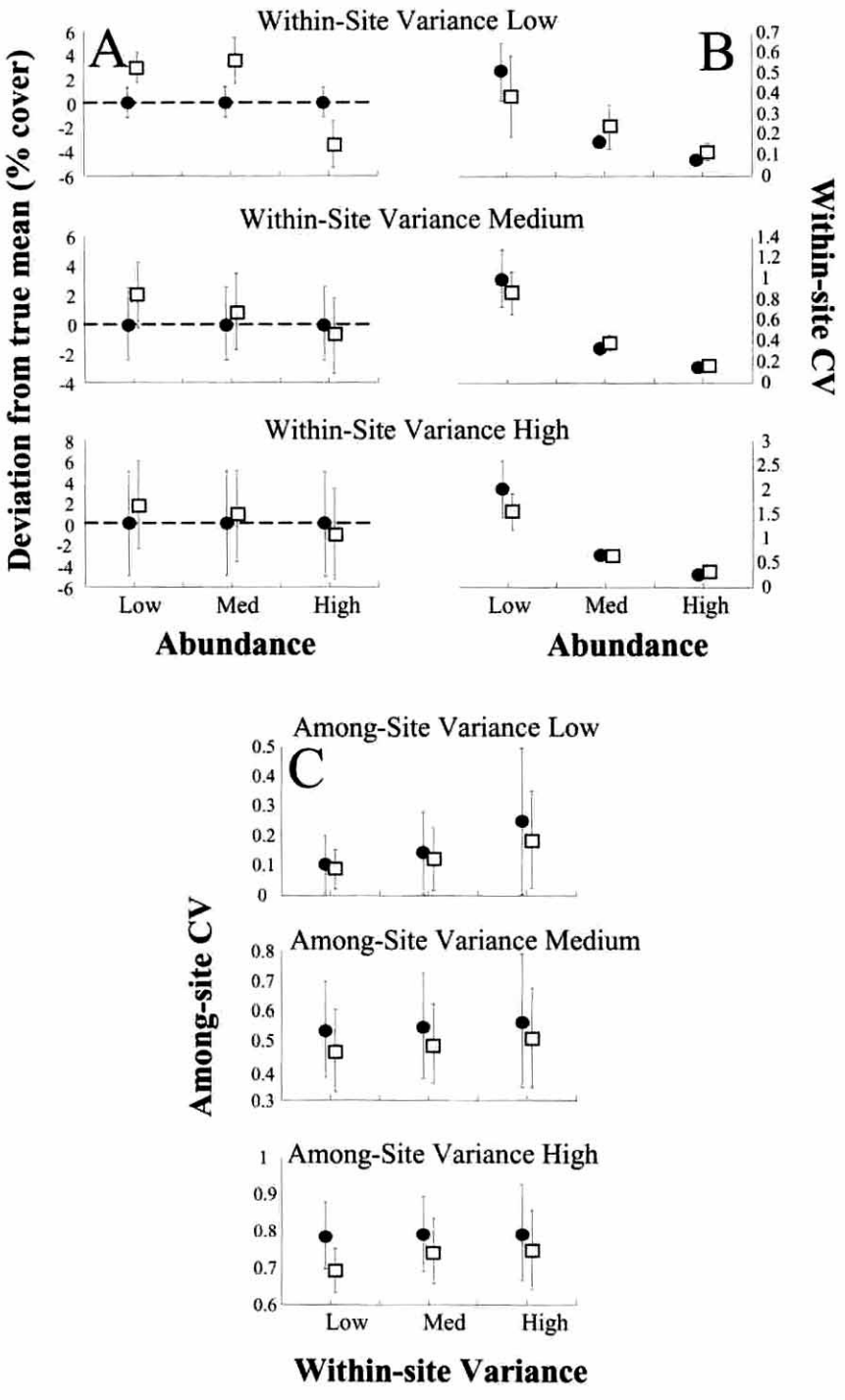

Fig. 4. Results from computer models simulating community sampling with both RPC (dark solid circles) and Coefficient (white squares) methods. (A) Deviations from the true (parameterized) means mean bottom cover. (B) Variation in bottom cover estimates among samples within each site (expressed as the coefficient of variation ± 95% confidence intervals). (C) Variation in bottom cover estimates among sites within each location (expressed as coefficient of variation ± 95% confidence intervals).

expected that the Targeted Sampling method, because of the large effort that went into choosing the best sample unit for each species, would be the most costly in terms of time and effort required to sample but provide the most accurate estimates of bottom cover, while the Coefficient method would require less time and effort but provide less accurate estimates. In contrast to our predictions, the results of both our field surveys and computer simulations suggest Targeted Sampling and Coefficient Sampling methods yield remarkably similar estimates of organism density and bottom cover, and provide similar abilities to detect changes in these esti-

mates over time. However, the two methods differed substantially in terms of the time and effort each required to sample these habitats. The Targeted Sampling method required both an additional diver and more time to complete the sampling during a single dive .Specifically, while the Targeted Sampling method required approximately 40-50 minutes for two divers to sample a site using all three sample units (swaths, quadrats, and point contacts), a single diver was able to complete all the sampling using the Coefficient method in approximately 30 min. This allowed the second diver to collect samples, deploy and collect oceanographic monitoring devices, or undertake a variety of other tasks that may be important to the study objectives. Therefore, we found the Coefficient method to be far cheaper in terms of time and effort required to sample, while providing similar benefits in terms of accuracy and precision.

We were surprised that, with the exception of juvenile kelp on only one sample date, these two methods did not differ in their abilities to detect changes in density over the three-year study for several reasons. First, the Coefficient method relies on a single sample unit (a 0.5 m^2 quadrat) to sample all organisms regardless of their size or abundance while the Targeted Sampling method relies on different sample units, each of which is specially chosen for the particular species and/or functional groups being assessed. This difference was especially relevant to *Macrocystis*, which occurs in densities of approximately one individual per 10 m^2 throughout this geographic range (Edwards 2004) and therefore should require a larger sample unit. As a result, data for *Macrocystis* obtained using the 0.5 m^2 quadrat consisted primarily of zeros and an occasional single individual, while the data collected using 20 m × 2 m swaths (40 m^2) provided data more similar to the actual site means. However, although the two methods used to sample *Macrocystis* differed in the total area sampled in each site by a factor of 24 (the Targeted Sampling method's swaths sampled a total area of 120 m^2 per site while the Coefficient method's quadrats sampled a total area of 5 m^2 per site), upon repeated sampling at multiple sites, the two methods yielded remarkably similar estimates of density.

As was the case for abundance estimates, our estimates of bottom cover and the ability to detect changes in bottom cover also did not differ between the two sample methods. This was perhaps more surprising than for density estimates that were obtained in similar, albeit different-sized, sample units. In contrast, the Target Sampling method relied on RPCs that require substantially more time and effort to sample than simple qualitative visual estimates. However, as with the quadrats, repeated sampling with the two methods yielded very similar estimates of bottom cover, but for a much lower cost in terms of personnel and time required for sampling for the Coefficient method. These findings were supported by the computer simulations, which found little to no differences in accuracy (deviations from the true mean) between the two sample methods. Therefore, our results support Braun-Blanquet and Pavillard's (1922) and Boudouresque's (1971) method of categorizing bottom covers into categories containing a range of values and transforming visual estimates of bottom cover to the median value within each category as a cheaper but just as effective method of quantifying bottom cover of benthic species. Consequently, if the goal of a study is to simply assess patterns of distribution and abundance of benthic kelp forest organisms or to evaluate changes in abundance through time, we believe that the Coefficient method may be just as effective as the Targeted sampling, which may be especially important when time is a limiting resource.

Although the Coefficient method may be better suited for environmental monitoring programs designed to track changes in organism abundance over time and where cost is a restrictive factor, it is not without its limitations. Because the Coefficient method provides a single numeric value (the median) to represent a range of possible bottom covers within each category (Boudouresque 1971), the ability to accurately describe small (i.e. within-category) differences in bottom cover and evaluate quantitative relationships among species within quadrats is greatly reduced or lost altogether. For example, if two samples are collected using Targeted Sampling (i.e. with RPCs) and these produce bottom cover estimates of 8% and 22%, they will yield a mean estimate of 15%, a standard deviation of 9.9%, and a coefficient of variation of 0.66. However, if these same two samples are collected using the Coefficient method, both estimates occur within Category 2 (6-25%, see Introduction) and will therefore be transformed to the category's mean value of 15%. Thus, when these two samples are averaged, they will yield the same mean bottom cover as the Targeted Sampling (15%) but will not exhibit variability between them. In contrast, two samples may also be similar in bottom cover but assigned to different categories, thus overestimating the variability between them. For exam-

ple, if two samples are collected using the Targeted Sampling and these produce estimates of 20% and 30%, they will yield a mean estimate of 25%, a standard deviation of 7.07%, and a coefficient of variation of 0.28. But, when these same samples are collected using the Coefficient method, they will produce estimates of 15% and 37.5% respectively, and yield a mean bottom cover of 26.25%, a standard deviation of 15.9%, and a coefficient of variation of 0.61. While this may not be problematic for environmental monitoring programs that seek to characterize ecosystem changes over large geographic areas, we believe that the Coefficient method may not be appropriate for studies that seek to elucidate ecological processes or describe patterns of organism bottom cover at much smaller scales, especially where patterns of variability are of central concern. Thus, the Coefficient methods my not be appropriate for use in experimental studies done at small scales where this variability is of central concern. In these instances, we recommend that the experimenter rely on traditional quantitative techniques such as those described in the Targeted Sampling method. However, once enough samples are taken to adequately describe the variability among quadrats (15 in this study), the Coefficient method appears to provide similar estimates of both mean bottom cover and variability in bottom cover within each site. Thus, this method may be appropriate for use in experiments done at larger scales where multiple samples can be taken and their estimates averaged, within each site. This conclusion is supported by the computer simulation models that found within-site variability for bottom cover of all three functional groups to be only slightly lower when estimated using coefficients than with RPCs, while among-site variability was similar between the two methods. This discrepancy, however, appears largely limited to organisms that occur in low abundance. Therefore, we recommend that a researcher about to begin a monitoring program carefully consider both the nature of the data and the primary objective, and then choose the most appropriate sampling design.

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