Comparison of Methods Used to Estimate Coral Cover
in the Hawaiian Islands

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Abstract – Characterization and comparison of reef coral communities throughout the broad geographic range of the Hawaiian Archipelago will require an extensive database on coral cover. Data on coral coverage is already in existence, but these data were taken by different methods and by different individuals over a period of many years. A comparison of these methods was undertaken in order to determine whether or not results of different techniques could be combined in an analysis of coral cover. Coral cover was estimated at 10 fixed sites in Kāneʻohe Bay, Oʻahu over a period of two days using nine methods widely used to measure coral cover in Hawaiʻi. All methods produced surprisingly similar results. Results indicate that each of the methods is appropriate for its intended purposes and all methods provide a good first estimate for the general characterization of coral cover on a reef. However, it has long been known that a large number of short "quick and dirty" transects will produce a better estimate of coral cover in a given habitat than a few highly detailed longer transects, so a method that yields more transects with the same amount of effort will be superior in quantifying coral cover in a given habitat.

The methods evaluated here were originally developed in response to the needs of specific investigations. Factors such as differences in question being asked (intensive or extensive surveys), constraints on field time or laboratory processing time, costs of hardware and software required, level of field experience of observers, utility of sampling regimes under various field conditions, need to archive images for future use, etc. led to the development of the different methods. Results of this investigation indicate that investigators who initially developed and implemented each method apparently had a solid "intuitive" grasp of how to develop a reasonable scheme that met their specific survey needs. These methods were widely used in the past and undoubtedly will continue to be used in the future, so it is of great value to know that all of them yield similar coral cover estimates. This study only compared transect methods and did not address the question of long-term monitoring design which has been considered elsewhere.

Introduction

Over the past three decades a series of methods have been used to estimate coral cover throughout the Hawaiian Archipelago. These methods vary in the cost of equipment required, the amount of time required to conduct the survey, and the time needed to analyze images and record data. Methodologies evolved over the past 30 years due to technical advances in photography, digital video and most recently digital photography.   Some methods are more appropriate for surveys over broad geographic areas while others are more suitable for intensive and detailed analyses of cover directed at coral community structure. The choice of method is very dependent on the question being asked. Some studies only involve measures of coral cover while others involve simultaneous measurements of factors such as coral, algae, fishes, invertebrates and rugosity. In these cases, the operational compatibility of the coral census method with other assessments influences method selection. But to what extent are all of these methods comparable? Can we legitimately combine coral cover measured by various methodologies? The purpose of this investigation was to evaluate the comparability of transect data developed using different methodologies used in the Hawaiian Archipelago to measure coral cover.

Methods

Nine methods that have been widely used in the Hawaiian Archipelago were selected for comparison. These are representative of methods that have been used previously in Hawaii, although there have been minor differences resulting from variations in number of points sampled, area sampled, type of images taken or length of transect. The time required by each method to run each transect, time required to process data and time to record the results were documented. Cost for hardware and software required by each method was also tabulated. Ten sites were selected in Kāneʻohe Bay for the inter-comparison experiment (Fig. 1, Table 1). Mean estimated coverage at different sites ranged from less than 10% cover to greater than 90% cover. For purposes of this study, observers highly skilled in a particular method were used to avoid methodological variability and different observers were used for each method. At each of the ten sites, 25 m transect lines were laid out and fastened to the bottom. Each method was run on each transect line over a two day period.
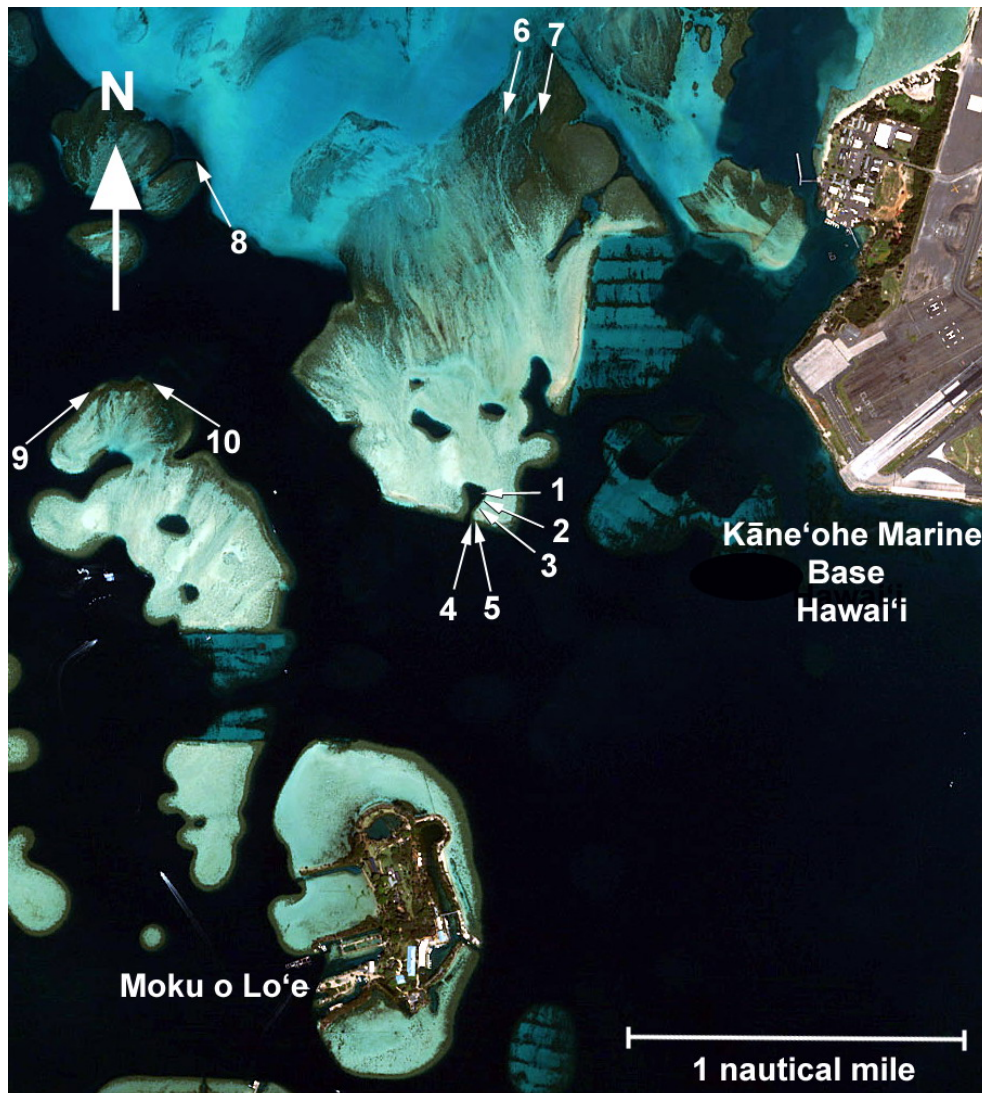

Fig. 1. Aerial view of Kāneʻohe Bay showing location of the 10 comparison sites.

Table 1. Location and depth of the study sites.

Site	Depth (m)	Latitude	Longitude
1	2	21°26.587'	157°47.168'
2	6	21°26.587'	157°47.168'
3	2	21°26.587'	157°47.168'
4	1	21°26.565'	157°47.189'
5	9	21°26.565'	157°47.189'
6	2	21°25.995'	157°47.204'
7	2	21°25.995'	157°47.204'
8	4	21°26.940'	157°47.748'
9	2	21°27.634'	157°47.817'
10	7	21°26.750'	157°47.639'

The nine methods that were compared are as follows:

1. Quadrat

The visual Quadrat method based on area estimates has been widely used in Hawai'i for the past 30 years (e.g. Maragos 1972, Jokiel and Coles 1974, Jokiel and Maragos 1978, Maragos and Jokiel 1986, Jokiel and Tyler 1992, Jokiel et al. 1993, Jokiel and Brown 1998) and pre-dates availability of video or reliable photographic methods. Coral cover is estimated using a 1 m^2 quadrat frame divided into 100 (10 x 10cm) smaller squares. The observer visually estimates coral cover *in situ* and records the data on an underwater writing slate. Coral filling one of the squares occupies 1% of the frame, so the observer uses the grid to estimate total area of each species encountered. A transect line is not required because the frame can be flipped 25 times to measure contiguous non-overlapping areas without reference to the line. In this study, the quadrat was moved successively along the entire 25 m transect line without overlap, encompassing a total area of 25 m^2. The coral coverage by species was estimated in each frame. During this study P. L. Jokiel made the measurements using this method.

2. Random

Various types of *in situ* random point sampling methods have been developed (Reed 1980). The most widely used random point intercept method currently used in Hawai'i is that adopted by NOAA as part of their fish habitat utilization studies (FHUS) as described at a website at http://ccma.nos.noaa.gov/ecosystems/coralreef/hi_rfh.html. This method uses a 1 m^2 quadrat divided into 100 (10 x 10cm) smaller squares. Sampling points are randomly chosen intersections of the strung lines of the quadrat. Each quadrat position along the transect line is randomly chosen before the diver enters the water such that there is one randomly placed quadrat frame within every 5 m interval along the transect. If the meter mark is an odd number, then the quadrat is placed on left side of the tape; if even, it is placed on the right. Twenty-five random points per quadrat are scored. The cover below each of the 25 random intercept points is scored as if looking at the quadrat in a two dimensional plane (i.e. as in a photograph). Percent cover

values are calculated by dividing the number of recorded points by the number of selected intersections. K. S. Rodgers made measurements using this method during this study.

3. Point-Line Intercept

Substrate type at sampling points is recorded along two 25 m transect lines spaced end to end with a three meter gap. At 50 cm intervals on the transect line data is recorded, yielding a total of 51 points per transects. Coral cover is recorded by species. Percent coral cover is determined by dividing the number of points recorded as coral by the total number of points and multiplying by 100. During this study G. Aeby made the measurements using this method.

4. CRAMP RAT

The Hawai'i Coral Reef Assessment and Monitoring Program (CRAMP) Rapid Assessment Technique (RAT) is a highly abbreviated version of the CRAMP monitoring protocol, consisting of a single fish transect, a single benthic transect, a rugosity measurement, a sediment sample and various qualitative habitat observations (Jokiel et al. 2004). The RAT is designed to produce quantitative spatial data that is consistent with and comparable to data taken at the permanent monitoring sites. The power of the RAT lies in large numbers of replicates taken over the spatial range of a given habitat. The assessment program expands the ability to describe habitats and spatial distributions of Hawaiian reef organisms in relation to various environmental factors. However, the assessment protocol requires a small fraction of the human effort and cost per site in comparison to the monitoring sites. Assessment data can be used with monitoring data for spatial comparisons.

Benthic cover is determined using high resolution digital images taken along a 10 m transect using an Olympus 5050 zoom digital camera with an Olympus PT015 underwater housing. The camera is mounted to an aluminum monopod frame, 1.7 m from the substrate to provide a 50 cm x 69 cm image. The 20 non-overlapping images from each 10 m transect are imported into an ecological analysis program (PhotoGrid 2002) where 50 randomly selected points are projected onto each image for a total of 1000 points per transect. Percent cover, richness and diversity of corals, algal functional groups and substrate cover are quantified.

Precision using photographic techniques was determined to be high (~95% similarity among observers) compared to *in situ* observations (Brown et al. 2004). Although initial costs are high, cost effectiveness surpasses visual techniques after only ten surveys (Brown et al. 2004). While post-processing time is involved, costly underwater dive time is greatly reduced with the use of this technique.   The method allows for archiving and data verification, which is critical in addressing further questions, and in quality control. Recent technological advances in digital still cameras have alleviated the disadvantage of limited image resolution. K. S. Rodgers made measurements using this method.

5. Video Transect

A digital video camera in an underwater housing is used to record the substrate along two 25m transects placed end to end with a 3 m separation. A red filter in the housing is used over the lens at depths greater than ~ 4m. The videographer swims approximately 1 m above the transect line with the camera lens pointing directly downward, and additionally records 360°

views of the surrounding area at the beginning and end of each transect line. The software program DVRaptor-RT Video (Canopus Corporation) is used to capture adjacent, non-overlapping still frames along the length of each transect line. Images are enhanced in ACDSee™ (ACDSystems) when needed to improve the quality of the images. The number of captured frames varied among the 20 transects at the 10 sites (range 29 – 36 frames/transect) in the present study due to variation in the height of the videographer (K.S. Rodgers) above the transect lines. Accordingly, the number of captured still frames randomly selected for analysis varied (range 16-25) so as to include 16m^2/transect benthic area (Kenyon et al. in press A). J. Kenyon analyzed selected frames for coral cover by species according to the method described in Kenyon et al. (2005).

6. Towed-diver

Towed-diver surveys have been widely used throughout Hawai'i by the Coral Reef Ecosystem Division (CRED) of NOAA's Pacific Islands Fisheries Science Center following the methods of Kenyon et al. (2005). Habitat digital still frames sampled from videotapes at 30 second intervals as the towboard moves over the bottom at ~ 0.8m/sec are analyzed for coral percent cover using the methods of Kenyon et al. (2005). In the present study, three photos were taken with an Olympus 5050 digital camera in an Olympus PT015 underwater housing to simulate images produced by the towed-diver method. One image was taken at the beginning and end of the first 25 m transect and one at the end of the second 25 m transect (i.e. three images over 50 m). This spacing and image area (~ 1m^2) is equivalent to that produced by the towed-diver method (Kenyon et al. in press A). The field survey was supervised on site by J. Kenyon and used her equipment. The processing of the images was carried out entirely by J. Kenyon.

7. Photoquad (Photographic Transect)

An Olympus 5050 digital camera with a wide-angle lens and an Olympus PT015 underwater housing was used to obtain the images.   The camera was positioned above a 1 m^2 quadrat strung into 100 subdivisions at the proper distance needed to include the entire frame in the photograph. Images were taken along the entire 25 m transect line without overlap. A total of 25 m^2 was used to visually determine the percent substrate cover.   The software program ACDSee™ 32 Browser is used for image viewing with data input directly into Microsoft Excel™. The amount of coverage of each substrate type is estimated in each subsquare, and then summed to determine the total cover for each species in a manner similar to the *in-situ* quadrat method. Coral cover is recorded by species. During this study the quadrats were photographed by F. Farrell with P. Jokiel moving the frame over the transect line. The laboratory analysis of the images was conducted by K. Uchino.

8. Estimate

In this method a visual *in situ* estimate of percent coral cover by species is visually recorded by a diver swimming along a transect 25 m in length and 5 m in width. The method requires an experienced observer. During this study K. S. Rodgers made the measurements using this method.

9. NOAA Ground Truth

NOAA's National Ocean Service Biogeography Team uses this method for field validation and accuracy assessment of benthic habitat maps (NOAA 2005, Monaco *et al*., 2005). The location of a sampling station for map accuracy assessment is determined using a stratified random sampling régime as per Congalton (1988), while stations used for field validation are selected based on specific features in the imagery, which are difficult to identify without further fieldwork. The stations are located using navigational GPS and marked with a temporary buoy. A 7 m radius around the marker delineates the area surveyed. Geomorphologic structure and biological cover based on the NOAA classification scheme are recorded (Coyne *et al*., 2003). Coral cover is estimated in 10% increments, which are subsequently placed into one of the following four categories: <10%, 10%-49%, 50%-89%, and 90%-100%. Thus, the estimated total coral cover may fall into only one of four categories, which might be termed "none", "low", "medium" and "high". This method requires a skilled observer, but takes very little time. For shallow sampling stations, the observer will often view the bottom through a "look box" from a boat or kayak without actually getting into the water. Deeper sampling stations or those with poor visibility are assessed by snorkel. Digital photographs of stations sampled by snorkeling are often collected. W. R. Smith made measurements for this investigation.

Statistical Methods

Species richness was examined using a General Linear Model (GLM) one-way ANOVA with number of species as the dependent variable (N=10 sites) and nine methods (Quadrat, Random, Point-line, CRAMP RAT, Video, Towed-diver, Photoquad, Estimate, and NOAA Ground Truth) as the factor. Transects at each of the 10 sites were averaged for methods using two 25 m transects (Point-line, video, towed-diver).

Comparing both coral cover and species richness data among methods utilized a one-way ANOVA. Percent coral cover was arcsin-square root transformed to meet the assumptions of normality and homogeneity of variances. Post-hoc multiple comparisons among means were conducted using a Tukey HSD test when ANOVA results detected significant differences among methods.

A ranking test was applied to the site data in order to determine whether or not any of the methods produced estimates that were consistently higher or consistently lower than the others. For each site, each method was ranked with a rank of 1 given to the method yielding the highest coral cover for the site and a rank of 9 to the method that gave the lowest coral cover for the site. Thus, a method that yielded the highest coral cover at all 10 sites would have an average rank of 1. A method that yielded the lowest coral cover at all 10 sites would yield a rank of 9. If all methods yielded the exact same number at each site then all methods would have a rank of 5. The rank data can then be analyzed statistically to determine if there was a consistent difference in the estimate of coral cover produced by any of the various methods.

Coral cover for each method was ranked from highest to lowest at each site. A one-way ANOVA was then conducted with untransformed ranks as the dependent variable and method as the independent factor. This procedure allowed a more appropriate comparison among the methods by separating out the effect of habitat.

The coral cover variance structure among methods was plotted to display which method generated the most variable data set and consequently the lowest statistical power to detect spatial differences.


Results

A comparison of the costs and time required for each method is presented as Table 2. The initial equipment cost varies by three orders of magnitude among methods. For example, the visual "Estimate" method takes one person several minutes and costs practically nothing while a "Towed-diver" survey requires two divers, two tow-boards, cameras, communication gear and a towing boat and crew. Considerable post-processing of the imagery is required for the video transect. A summary of the total coral cover data for each method at each site is shown as Fig. 2. Note the high variance of all methods due to the inherent "patchiness" of reef coral communities. Thus repeated measurements by the same method over the same transect will not yield the same number each time. Coverage by species for each method is shown in Table 3. A summary of the number of coral species measured by each method is shown in Table 4. The values for coral cover are for a single site (n=1). Sub-samples are not independent estimates, so the error bars are only useful for showing the high variance encountered in a coral reef environment. Running the same method over the same transect a number of times will give a highly variable result (e.g. see Brown et al. 2004).

Table 2. Summary table describing main features and costs for each method.

Method	Equipment	Data Record	Transect Length	Number of Samples per site	Points per Sample	Approx. Area (m^2)	Survey Time (min)	Lab Analysis (min)	Spread Sheet Data Entry (min)	Total Time (min)	Equipment Cost (US Dollars)
Quadrat	1m^2 quadrat, writing slate	*in situ*	25 m	25	100	25	20	0	5	25	$20
Random	transect line 1m^2 quadrat, writing slate	*in situ*	25 m	5	25	5	15	15	1	31	$20
Point-line	transect line, writing slate	*in situ*	two 25 m lines	2	51	50	20	0	5	25	$20
CRAMP RAT	transect line digital camera, PhotoGrid Software	Lab. Computer System	10 m	20	50	20	15	40	10	65	$700
Video	transect line video camera, D/V Raptor, CPCe Software	Lab. Computer System	two 25 m lines	34-47	50	50	5	65	5	75	$1,500
Towed-diver	digital camera, Sigma Scan software, tow-board system.	Lab. Computer System	approx. one image per 25 m	3	50	3	3	5	5	13	$2,500
Photo-quad	transect line 1m^2 photoquad, camera	Lab. Computer System or Projector	25 m	25	100	25	15	35	5	55	$700
Estimate	transect line writing slate	*in situ*	25 m	1	estimated range	25	3	0	1	4	$2
NOAA Ground Truth	writing slate	*in situ*	7 m radius	1	estimated range	154	3	0	1	4	$2
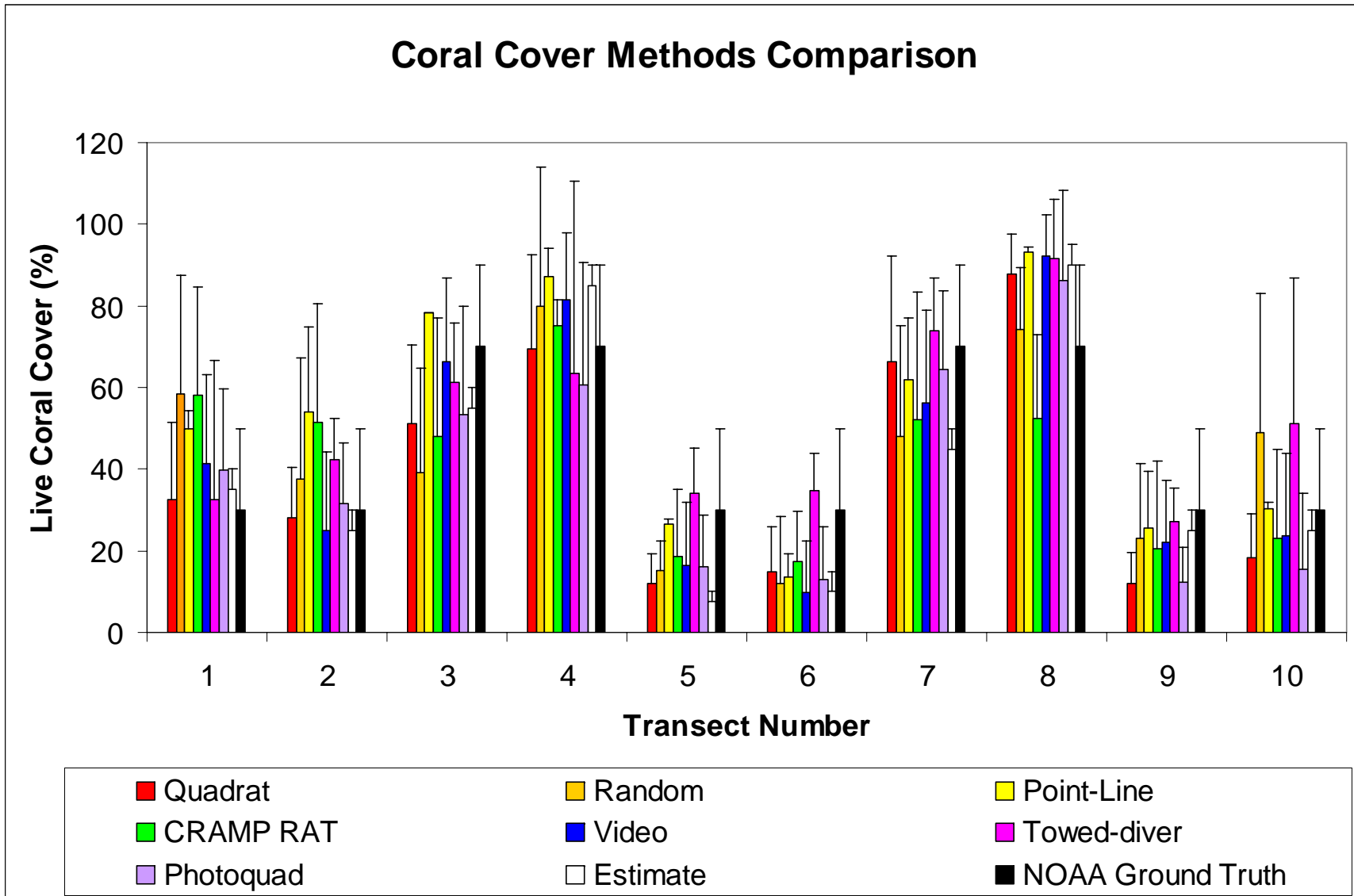
Fig. 2. Error bars for the first 7 methods (rainbow colors) are Standard Deviations. Error bars for the last two methods (white for Estimate and black for NOAA Ground Truth) represent estimated range.

**Table 3.** Coverage by species for each method at each site.

Montipora capitata

	Quadrat	Random	Point-line	CRAMP RAT	Video	Towed-diver	Photoquad	Estimate	Ground Truth
1	15	4	25.5	30.7	20.1	22.8	20	20.0	15.0
2	21	15	17.6	30.6	9.4	8.8	23	10.0	18.0
3	37	22	53.9	27.4	44.1	42.7	39	25.0	35.0
4	29	54	39.2	33.7	37.6	20.1	30	40.0	42.0
5	9.9	15	21.6	16.8	14.7	34.9	12	3.5	21.0
6	8.1		8.8	1.4	6.7	15.3	7	4.0	15.0
7	27	26	18.6	40.7	21.1	3.4	44	10.0	7.0
8	2.3	4	5.9	2.1	8.9	20.1	6.5	25.0	56.0
9	8.1	14	16.7	14.2	16.2	16.7	9	9.5	15.0
10	8	33	7.8	16.1	10.4	42.5	11	15.0	21.0

Porites compressa

	Quadrat	Random	Point-line	CRAMP RAT	Video	Towed-diver	Photoquad	Estimate	Ground Truth
1	18	14	24.5	27.5	21.2	9.9	20	15.0	15.0
2	16	22	36.3	20.9	15.5	33.7	8.4	15.0	12.0
3	14	17	24.5	20.9	22.4	18.7	14.2	30.0	35.0
4	41	26	48.0	41.4	43.8	43.4	30.4	45.0	28.0
5	1.8		3.9	1.8	1.6		3.8	4.0	9.0
6	1.1	2.4	1.0	1.5	0.2	0.7	0.7	2.0	9.0
7	39	21	41.2	10.4	34.0	70.5	20.6	25.0	63.0
8	84	68	85.3	48.8	83.3	68.8	79.4	65.0	14.0
9	3.5	7.2	7.8	5.2	4.9	9.1	2.9	15.0	15.0
10	10	16	21.6	7.0	13.3	8.8	4.9	10.0	9.0

Porites lobata

	Quadrat	Random	Point-line	CRAMP RAT	Video	Towed-diver	Photoquad	Estimate	Ground Truth
1					0.1				
2									
3									
4									
5							0.7		
6	5.2	8.8	2.9	3.8	2.8	1.3	5.2	4.0	6.0
7	0.1		1.0	0.1	0.7		0.3	9.0	
8			2.0						
9									
10	0.1								

Pocillopora damicornis

	Quadrat	Random	Point-line	CRAMP RAT	Video	Towed-diver	Photoquad	Estimate	Ground Truth
1	0.03								
2	0.02								
3	0.02		0.1						
4							0.1		
5	0.2		1.0	0.1	0.1		0.1		
6	0.2	0.8	1.0		0.1		0.3		
7	0.1		1.0	0.2	0.3		0.1	1.0	
8	0.1			0.2	0.1				
9	0.3	1.6	1.0	0.1	0.7	1.4	0.4	0.5	
10			1.0				0.1		

Pocillopora meandrina

	Quadrat	Random	Point-line	CRAMP RAT	Video	Towed-diver	Photoquad	Estimate	Ground Truth
1									
2									
3									
4					0.2				
5									
6					0.1		0.02		
7		1.6							
8	0.2						0.3		
9							0.1		
10									

Pavona varians

	Quadrat	Random	Point-line	CRAMP RAT	Video	Towed-diver	Photoquad	Estimate	Ground Truth
1									
2									
3									
4									
5									
6									
7									
8	1	1.6		1.1					
9	0.02								
10									

Fungia scutaria

	Quadrat	Random	Point-line	CRAMP RAT	Video	Towed-diver	Photoquad	Estimate	Ground Truth
1									
2									
3									
4									
5									
6									
7									
8									
9	0.1								
10									

Montipora patula

|	Quadrat	Random	Point-line	CRAMP RAT	Video	Towed-diver	Photoquad	Estimate	Ground Truth
1									
2									
3									
4									
5									
6									
7									
8	0.2	0.8		0.1		2.8			
9	0.4				0.3				
10									

Outcome of statistical analyses.

　　　Measured species richness (Table 4, Fig. 3) differed significantly among methods ($F_{8,81}$=3.2, p=0.003). The "Quadrat" method detected the highest number of species while the "NOAA Ground Truth" and "Towed-diver" methods showed the lowest number of species. The "Quadrat" method detected a significantly greater number of species (Fig. 3) than the other methods for a number of reasons. In the first place, this method surveys every coral within the 25 m² area. Methods that involve sampling a certain number of points generally will miss rare species. The "Quadrat" method involves close and direct observation of the corals by a diver who can easily detect corals such as *Pavona varians* and *Fungia scutaria* that typically grow in crevices and shaded areas that often do not show on image analysis. Close inspection by the diver allowed easy recognition of *Montipora patula*, which often cannot be differentiated from *Montipora capitata* in images. The Quadrat method requires an experienced coral reef ecologist as observer, but clearly will produce a more complete estimate of species diversity. The "Ground Truth" and "Towed-diver" methods require viewing from a greater distance and were significantly lower in their ability to detect small, uncommon or cryptic species (Fig. 3), while the remaining six methods showed no significant differences.

Table 4. Number of coral species recorded per site by each method.

	Species Recorded Per Transect								
Site No.	Quadrat	Random	Point-line	CRAMP RAT	Video	Towed-diver	Photoquad	Estimate	NOAA Ground Truth
1	3	2	2	2	3	2	2	2	2
2	3	2	2	2	2	2	2	2	2
3	2	2	2	3	2	2	2	2	2
4	2	2	2	2	2	2	3	2	2
5	3	1	3	3	3	1	4	2	2
6	4	3	4	3	5	3	5	3	3
7	4	3	4	4	4	2	4	4	2
8	5	4	3	5	3	3	3	2	2
9	6	2	2	3	4	3	3	2	2
10	3	2	3	2	3	2	3	2	2
mean	**3.5**	**2.3**	**2.7**	**2.9**	**3.1**	**2.2**	**3.1**	**2.3**	**2.1**
S.D.	1.2	0.8	0.8	0.9	0.9	0.6	0.9	0.6	0.3
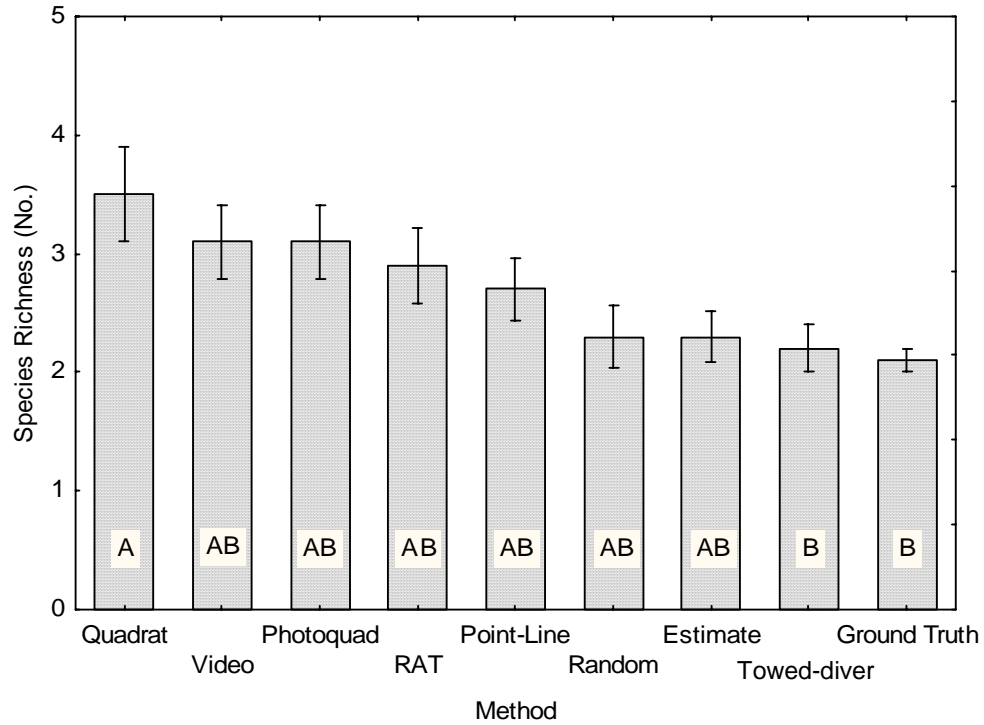
Fig. 3. Average species richness for each of the benthic survey methods (N=10). Mean number ± 1 SE. The same letter denotes homogeneous means using a Tukey HSD post-hoc test on square root transformed data ($F_{8,81}$ = 3.2 p=0.003).
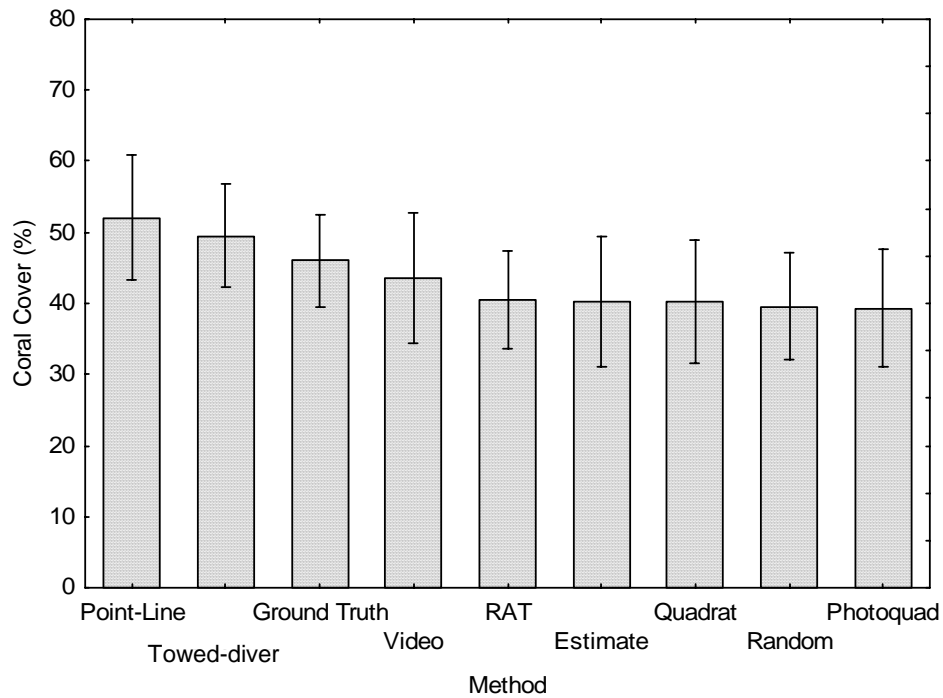

Fig. 4. Mean coral cover for the 10 sites as measured by each of 9 methods (±S.D.) Mean number ± 1SE. No significant differences among methods were detected using a Tukey HSD post-hoc test on arcsin-square root transformed data ($F_{8,81}$ = 0.38 p =0.93).

Table 5. Mean rank scores and mean % coral cover (mean of 10 sites) for each method.

transect	Quadrat	rank	random	rank	point-line	rank	CRAMP RAT	rank	Video	rank	Towed-diver	rank	Photoquad	rank	Estimate	rank	NOAA Ground Truth	rank
1	32.6	7	17.7	9	50.0	2.0	58.2	1.0	41.4	3.0	32.7	6.0	39.8	4.0	35.0	5.0	30.0	8
2	37.0	5	37.6	4	53.9	1.0	51.5	2.0	24.9	9.0	42.4	3.0	31.6	6.0	25.0	8.0	30.0	7
3	51.1	7	39.2	9	78.4	1.0	48.4	8.0	66.5	3.0	61.3	4.0	53.3	6.0	55.0	5.0	70.0	2
4	69.6	7	80.0	4	87.2	1.0	75.1	5.0	81.6	3.0	63.5	8.0	60.8	9.0	85.0	2.0	70.0	6
5	11.9	8	15.2	7	26.5	3.0	18.7	4.0	16.4	5.0	34.9	1.0	16.1	6.0	7.5	9.0	30.0	2
6	14.6	3	12.0	6	13.7	4.0	6.7	9.0	9.8	8.0	17.3	2.0	13.2	5.0	10.0	7.0	30.0	1
7	66.4	3	48.0	8	61.8	5.0	51.5	7.0	56.1	6.0	73.9	1.0	64.5	4.0	45.0	9.0	70.0	2
8	87.8	5	74.4	7	93.2	1.0	52.3	9.0	92.4	2.0	91.7	3.0	86.2	6.0	90.0	4.0	70.0	8
9	12.4	9	23.2	5	25.5	3.0	19.5	7.0	22.0	6.0	27.2	2.0	12.4	8.0	25.0	4.0	30.0	1
10	18.2	8	48.8	2	30.4	3.0	23.1	7.0	23.6	5.0	51.2	1.0	15.5	9.0	25.0	6.0	30.0	4
sum	401.6	62.0	396.1	61.0	520.6	24.0	405.0	59.0	434.7	50.0	496.1	31.0	393.4	63.0	402.5	59.0	460.0	41.0
mean	40.2	6.2	39.6	6.1	52.1	2.4	40.5	5.9	43.5	5.0	49.6	3.1	39.3	6.3	40.3	5.9	46.0	4.1
SD	27.3	2.1	23.8	2.3	27.9	1.4	21.9	2.8	29.1	2.3	23.1	2.3	26.0	1.8	28.7	2.3	20.7	2.9

Overall mean coral cover measured at the 10 sites (Fig. 4) was not significantly different among methods ($F_{8,81}$ = 0.38 p =0.93), but differences were detected through use of the ranking test (Fig. 5). Mean rank scores are shown in Table 5. The ranking analysis detected a significant difference among methods in terms of a consistent coral cover pattern ($F_{8,81}$ = 4.0 p <0.001). The "Point-Line" method typically ranked higher (lower numbered rank) at each site followed by the "Towed-diver", "NOAA Ground Truth", "Video", "RAT", "Estimate", "Random", "Quadrat", and "Photoquad" method. The "Point-Line" method probably gives a slightly higher cover estimate because wave action tends to move the transect line slightly until it catches on a coral. All points measured by the method are taken directly under the transect line, so the ranking score was significantly higher. The "Point-Line" method was statistically similar to the "Towed-diver", "NOAA Ground truth", "Video", and "RAT" methods. The "Estimate", "Random", "Quadrat", and "Photoquadrat" methods, however, grouped together and ranked statistically lower at each of the ten sites. Note that there is considerable overlap between the groups A and B (Fig. 5), so distinctions are not clear statistically.
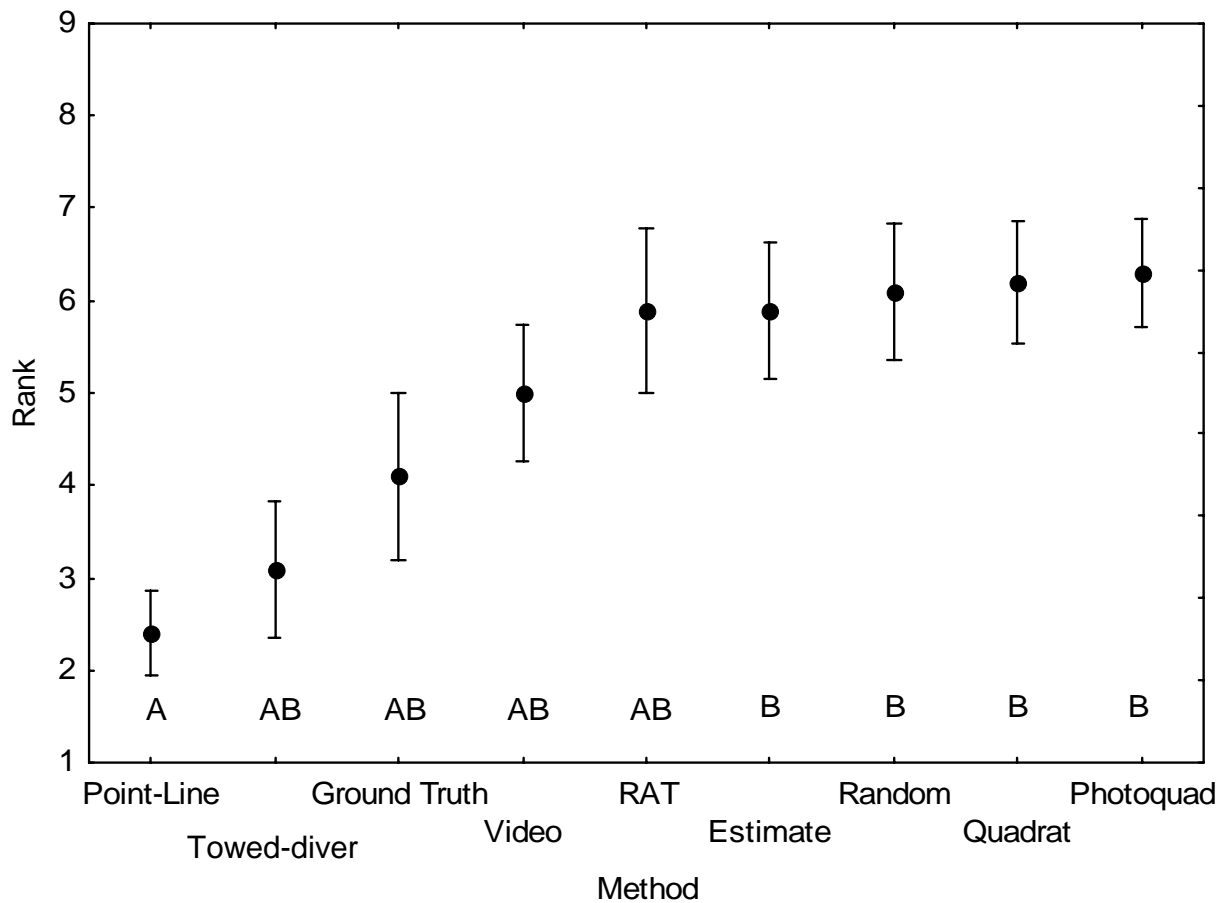
Fig. 5. Average ranking of coral cover at each site for the nine benthic survey methods (N=10). Mean number ± 1 SE. The same letter denotes homogeneous means using a Tukey HSD post-hoc test on raw data ($F_{8,81}$ = 4.0 p <0.001). Methods in group A have similar means to others in that group, but not to those in group B. Those in group B have means that are similar but statistically different from those in group A. Methods labeled AB have means statistically similar to those in both groups A and B.
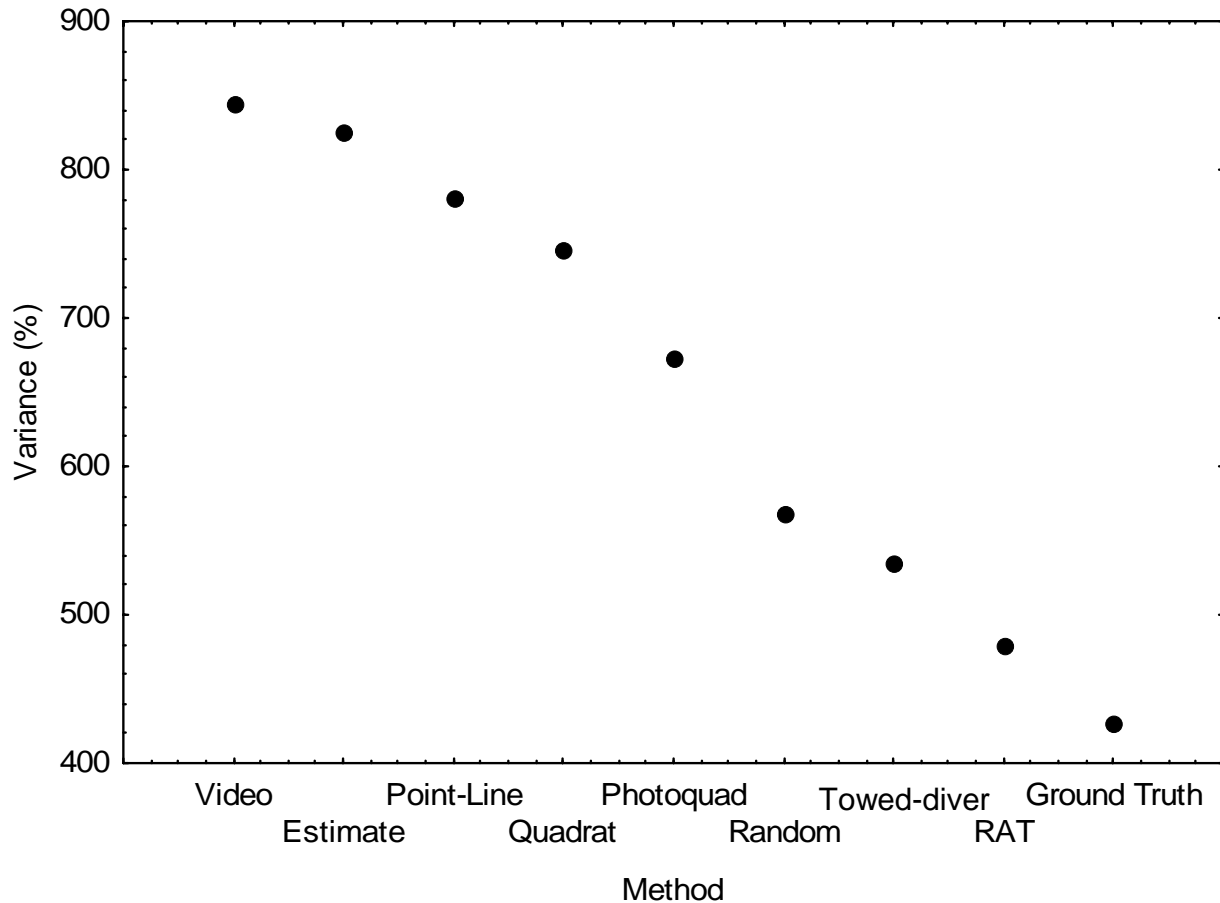
Fig. 6. Variance (%) for each of the benthic survey methods (N=10).

There is a growing recognition of the importance of power analysis and sample size calculation for the proper design of monitoring and assessment programs. Statistical power of a statistical analysis is a function of sample variance and sample number. Thus, variance estimates determined in this comparison study are useful in determining sample size needed using different methods and thereby can help in the design of future surveys. The variance structure among methods (Fig. 6) showed that the "Video" method had the highest variance for the ten sites and therefore, lowest statistical power to detect differences among sites. In contrast, the "NOAA Ground Truth" protocol had half the variance among the sites/transects. However, this difference is most likely an artifact due to the limited number of coral cover categories used in this method. The "RAT" method used high resolution digital still images, but otherwise was similar to the "Video" approach in terms of image analysis and substrate categorization. The "Video" technique covers a larger area (50 m) with 234 to 247 image subsamples within this distance. In contrast the RAT covers a shorter distance (10 m) and covers the entire area sampled, using 20 non-overlapping images. Thus, there is higher variability in the "Video" method is likely due to the larger area being subsampled. In addition, the lower image resolution for the "Video" method may also be a factor in producing higher variability in the estimate.

Discussion

Results of this investigation indicate that investigators who initially developed and implemented each method apparently had a solid "intuitive" grasp of how to develop a reasonable scheme that met their specific survey needs. All of the methods yield comparable estimates for coral cover. Each method has strengths and weaknesses and no one method will fit all research needs. The methods evaluated here were originally developed in response to the needs of specific investigations. Factors such as differences in question being asked (intensive or extensive surveys), constraints on field time or laboratory processing time, costs of hardware and software required, level of field experience of observers, utility of sampling regimes under various field conditions, need to archive images for future use, etc. led to development of diverse methods. These methods were widely used in the past and undoubtedly will continue to be used in the future, so it is of great value to know that all of them yield similar coral cover estimates.

Results of this study are generally consistent with results of other studies comparing methodology. Coral cover data inevitably show very high variance due to inherent "patchiness" of reef coral distributions, so even repeat sampling of the same transect with the same method will produce quite variable results. From a statistical point of view it appears that no one method was sufficiently different from the other methods based on the various characteristics evaluated in this study (Table 6). For example, some methods (e.g. Point-Line) documented high values in one area (e.g. coral cover rank), but generated moderate values for other characteristics (e.g. species richness). Other protocols (e.g. Estimate) spanned the range of category values, but did not represent the extreme for any one particular parameter. Finally, methods such as "Random" recorded moderate values for all of the characteristics

Table 6. Summary of qualitative characterization of coral cover methods based on species richness, coral cover ranking, and variance.

Method	Species Richness[1]	Coral Cover Rank[2]	Variance[3]
CRAMP RAT	Medium	Medium	Low
Estimate	Medium	Low	High
NOAA Ground Truth	Low	Medium	Low
Photoquad	Medium	Low	Medium
Point-Line	Medium	High	Medium
Quadrat	High	Low	Medium
Random	Medium	Low	Medium
Towed-diver	Low	Medium	Medium
Video	Medium	Medium	High

[1]Based on groupings of means in multiple comparison test
[2]Based on groupings of means in multiple comparison test
[3]Based on the following categories (High>800, Medium 500-800, Low<500)

Ideally, the optimal method would document higher species richness for biodiversity considerations, rank in the middle in terms of coral cover for good precision, and have low variance for high statistical power. Perhaps the closest method is the CRAMP RAT, but how well does this protocol really characterize the actual substrate compared to the other methods? Answering this question would require knowing the entire population under consideration. Therefore any of these methods appear to be adequate for relative comparisons both spatially and temporally.

Results of this investigation indicate that all of the methods used in the comparison are appropriate for their intended purposes and all provide a good first estimate for the general characterization of coral cover on a reef. This inter-comparison did not detect any consistent differences in the estimate provided by each method. However, it has long been known that a large number of short "quick and dirty" transects will produce a better estimate of coral cover in a given habitat than a few highly detailed longer transects (e.g. Kinzie and Snider 1978, Brown et al. 2004), so a method that yields more transects with the same amount of effort will be superior in quantifying coral cover in a given habitat.

Numerous visual surveys of coral cover have been conducted in the past, but the information obtained has been used sparingly in the literature. In some situations, visual estimates can be more reproducible and more accurate than random-point sampling (Dethier et al., 1993). However, there is a general reluctance to place reliance on subjective visual assessments, although Kenchington (1978) indicated that it should be possible to develop training procedures and scales of assessment which enable valid comparisons to be made of coral cover in space and time. Results of this investigation support the view of Kenchington (1978) in that observers with extensive experience in quantitative assessments of coral cover produced visual estimates that were similar to results of techniques that require much more effort. Even the "NOAA Ground Truth" method, which is restricted to scoring on a scale of four divisions ranked well against the other methods.

The classic "Quadrat" method has been in use in Hawai'i for nearly 40 years and is simple and inexpensive to use but requires a highly experienced observer. This method is especially attractive because of the large sample size (25 m^2, each with 100 squares = 2500 sampling units) compared to other methods. The proximity of the observer to the substratum and the large sample area yields a much better estimate for small or rare coral species. The ability of the "Quadrat" method to detect species allows coral abundance to be classified objectively (Jokiel and Maragos 1978) according to a system such as dominant (>10% cover), abundant (<1.0 to 10 % cover), "common" (<0.1 to 1.0% cover), or "rare: (< 0.1% cover). "Very rare" species can be defined as species not occurring in any quantitative sample, but noted in the area.

The use of towed-diver surveys was inaugurated in 1990 to assess those benthic variables considered to be important to lobster habitat on three emergent banks in the Northwestern Hawaiian Islands (Parrish and Polovina 1994). Since that time the method has evolved under the guidance of the Coral Reef Ecosystem Division at NOAA's Pacific Islands Fisheries Science Center in response to advances in videographic and georeferencing technology and has been adapted for mesoscale assessment of coral reef benthic habitats throughout the insular U.S. Pacific. A primary strength of towed-diver surveys is their ability to assess the major benthic components and condition of reef habitats over spatial scales substantially greater than can be observed and documented by free-swimming divers. A typical towed-diver survey covers up to 3

km, and 6 surveys can usually be conducted each field day. The method is particularly useful for assessing remote areas that can only be visited infrequently and for short durations, where more limited sampling by free-swimming divers may not adequately characterize the diversity of habitats. Because the divers are towed by a surface boat, they are able to work in sea conditions of swell or surge that are too dangerous for free-swimming divers or their support boat, and can thus provide data for habitats such as windward exposures that are otherwise rarely accessible (e.g., Kenyon et al. 2005, Kenyon et al. in press a, b). They provide a permanent visual record that is amenable to re-sampling. Because the imagery is linked to geographical position by way of a GPS receiver onboard the tow boat, a survey can be sub-sampled for any spatial interval that may be of interest. A primary limitation of interpreting visual information from a towed camera is the loss of taxonomic resolution, as is seen in reduced species richness in the present study relative to most other techniques (Table 4, Fig. 3). Field equipment as well as computer equipment needed to analyze imagery is expensive (Table 2), realistically limiting this method to programs with large budgets. Field and computer personnel require special training, the former to ensure safety and accuracy, the latter to ensure consistency and reproducibility.

The "Video" method evaluated in the present study was developed for use in benthic assessment surveys in the Northwestern Hawaiian Islands by a single diver tasked with estimating multiple parameters relevant to coral communities during one dive per site per year. The short field survey time required compared to most other methods in the present study (Table 2) is well suited to maximizing the time available to assess other coral parameters including site species richness, colony abundance and density, and size class distributions. It can also be implemented by an experienced diving assistant without expertise in the identification of marine organisms. The permanent visual record allows comparison between observers at a later date. However, as seen in the present study, efficiency of field data collection is offset by substantial post-processing time (Table 2). Though species richness in the present study was congruent with other methods (Table 4, Fig. 3), the "Video" method is not as adept at reporting small, cryptic, or encrusting taxa (e.g., *Pavona varians, Cyphastrea, Leptastrea*) when they occur as are most *in situ* methods.

Other workers in Hawai'i have used techniques that are similar, but not identical to those evaluated in this investigation. Dimensions of photo-transects less than the 1 m^2 used in this investigation have been adopted by some investigators in order to accommodate the image taken by 35 mm cameras. Coles (1984) used a fixed photoquadrat measuring 1 m x 0.66 m marked by fixed galvanized iron bolts, which serve as a platform for a camera frame. Images taken with a Nikonos camera having a 28 mm wide angle lens at a focal distance of four feet correspond to the field of view of 0.66 m^2 for each quadrat. Percent coverage of each species on each quadrat are determined by the point intercept method using 485 points superimposed on the projected image. Likewise, Dollar and Grigg (2004) used a 1 m x 0.66 m^2 image area to accommodate the field of a wide angle lens, but used a visual estimate based on a grid of 100 subdivisions similar to that used in this study. Other variations in the different methods have been employed, but generally methods used previously are encompassed by the type of measurements evaluated in this investigation.

This study focused on techniques used in Hawai'i. Other studies have compared techniques not widely employed here. These include comparison of line-intercept (Carleton and Done 1995) or chain method (Rogers 1999) with video, photographic, and estimated cover. The major conclusion of these studies is that techniques that involve a three dimensional component (line-intercept, chain method) will give a different estimate than methods that measure in a

planar view. All of the techniques used commonly in Hawai'i report a planar area for coral coverage. Relatively few coral species are found in Hawai'i. Low coral diversity might have contributed to the limited differentiation among methods in this study. Similar evaluations in highly diverse reef systems might show greater differences between the techniques. Further, gorgonians and *Acropora* thickets are not found on shallow Hawaiian reefs, so investigators here do not have to deal with a large vertical dimension.

Monitoring.

The present investigation only compared methods suitable for initial site characterization along a single transect. Comparison and evaluation of monitoring techniques designed to detect changes in coral cover is a far more complex issue. The choice of sampling design for a reef monitoring project is determined principally by the question to be answered and the sampling accuracy and precision required (Green and Smith 1997). Such studies require rigorous sampling design and analysis in order to produce the statistical power needed for the experimental design. Statistical power is the probability of rejecting the null hypothesis or the confidence in accepting null hypotheses of no change over time for key parameters such as coral percent cover (Green and Smith 1997). The development and testing of the monitoring design employed by CRAMP has already been discussed in Brown et al. (2004) for Hawaiian reefs. During extensive studies in 1998, Brown et al. (2004) found that repeated sampling of conventional transects or quadrats showed unacceptably high variation unless fixed transects were established to allow precise repositioning. Statistical power to detect change in coral cover decreased dramatically when coral cover was greater than 20%. Longer transects (e.g. 25m and 50m) fared well in homogeneous substrates but shorter transects (e.g. 10m) were more appropriate in heterogeneous habitats. Variability between observers analyzing the same data was low in comparison to other sources of error. Visual estimation techniques were cost effective but did not permit data archiving of digital images. Digital imaging had the highest initial monetary investment but yielded the largest quantity of data per unit of field effort. These results were used to establish the standard CRAMP monitoring sites that can detect less than a 10% change in coral cover with high statistical power (P>0.80) using 50 points per frame, 20-30 frames per transect and 8-10 transects of 10 m in length per site. The power of this design increases over time with repeated surveys. In the CRAMP protocol, fixed photoquadrats with high precision are also used to address questions on recruitment, growth and mortality. The recent production of precise habitat maps along with introduction of the geographic positioning system (GPS) and availability of geographic information systems (GIS) has opened the possibility of using stratified random sampling of coral communities in Hawai'i as an alternative to fixed transects, but again this approach requires a large number of transects per habitat to detect change due to the inherently high variance of coral coverage data.   An extensive summary and review of all aspects of coral reef monitoring (questions, techniques and design) has been compiled by Hill and Wilkinson (2004).

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