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A “quick and clean” photographic method for the description of coral reef habitats

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ABSTRACT

The use of scuba-based photo/video methods for characterizing coral reef habitats has gained increased popularity within the last decade, but few work examined the potentiality of surface photography to provide accurate, reliable habitat profiles in contrasted habitats. Photo transects were thus conducted by snorkeling in contrasted reef biotopes (reef flat, reef crest, sandy bottom) from the south-west lagoon of New Caledonia, to develop and test a “quick and clean” approach suitable for addressing monitoring as well as research-oriented programs. Pictures were taken by a snorkeler from the surface over twelve (20×1 m) reef crest/reef flat/soft bottoms transects using a standard 8 Mpixel digital-camera with underwater housing. Habitats were characterized from percent covers for 15 categories of local habitat variables related to sediment type and substrate coverage. Exhaustive area analyses using computer-assisted manual digitalizing were used to provide reliable habitat profiles from the digital pictures. Results were subsequently compared with surface estimates derived from random stratified point count techniques, for numbers of points comprised between 1 and 99 per m^2. Sampling-based randomization techniques allowed us to provide robust, reliable statistical estimates of accuracy and precision over 1000 randomized bootstrap replicates per transect. Results emphasized high accuracy and precision at transect scale whatever the reef biotopes considered, with maximum deviations from reference values of ~1 percent cover in almost all cases and associated variances <0.001. From a practical point of view, using a 9 points/m^2 ratio clearly provided reliable, quantitative descriptions of our reef transects (maximal errors <1.5 percent cover with 95% confidence level). Cost-effectiveness is high, with 15-30 minutes/transect from field data collection (<10 min) to computation of final percent covers (10-20 min). The method outlined in this paper thus combines high statistical efficiency and logistical ease, and could be used to address more functional perspectives.

1. Introduction

Coral reefs are complex ecosystems that support a high diversity of habitats, whose structure/dynamics are generally expected to play a key role in shaping the associated biological communities (Roberts and Ormond, 1987; Jones and Syms, 1998). With the worldwide decline of coral reefs and related fisheries, assessment of habitats has recently become a research priority through a variety of national/international monitoring programs (Hodgson, 1999; Hughes and Connell, 1999; Brown et al., 2004). The data collected should thus provide baseline information on reefs status in the framework of global changes (e.g. to distinguish between natural and human-induced variability) and allow comparisons over regional and global spatiotemporal scales (Hodgson and Liebeler, 2002).

As the choice of a method strongly depends on the specific question to be answered, various techniques were developed in the last decades to assess reef habitats (see reviews in English et al., 1997; Hill and Wilkinson, 2004). Habitat descriptions traditionally rely on estimations of environmental variables using scuba diving, or, more recently, remote operated vehicles (Manriquez and Castilla, 2001; Lam et al., 2006) and, at larger scales, remote sensing (Andrefouet and Riegl, 2004). Qualitative and/or quantitative estimations of substrate variables (e.g. coral, sediment, algae, macrophytes etc.) are generally obtained from a broad array of techniques including direct underwater observation, photographic or video recordings along line transects/quadrats with different size/area. Constraints in terms of time required (fieldwork/laboratory processing), levels of experience and associated costs (equipment/human) strongly differ between methods, thus influencing the outcome of the surveys: while some methods provide accurate, fine-scale data that are suitable for scientific research, some others provide less-detailed information over broader scales that are more appropriate for management purposes (Hill and Wilkinson, 2004).

With the recent technological advances, the use of digital equipment in coral reef monitoring has become more and more popular. Unequivocal, practical advantages partly explain their success: as they require far less time under water than traditional visual methods, photography and video constitute cost-effective methods that greatly reduce time spent in the field (Aronson et al., 1994). Recent work also highlighted that these methods can produce higher precision in terms of

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detecting changes in coral communities than visual methods (Ninio et al., 2003; Brown et al., 2004; Lam et al., 2006).

Photo/video may also constitute powerful tools for studies addressing species/habitat relationships (Friedlander and Parrish, 1998; Kollmann and Stachowitsch, 2001; Hill and Wilkinson, 2004), as their ability to provide estimates of habitat variables –a key point for ecological approaches– can be partly mediated through image processing (e.g. number of frames/data points per frame, Houk and Van Woesig, 2006). Formal testing of their efficiency is still difficult, as it requires intensive, highly time-consuming field work in contrasted reef habitats. In practice, most studies addressing photo/video methods focus on a restricted set of habitat variables, recorded over a limited combinations of biotopes and stations. While classical, statistical estimates of precision and associated variability obtained within this framework can be of low intrinsic value, specific methodological approaches may help to overcome the limitations associated with restricted datasets. Randomization techniques (e.g. bootstrap resampling techniques, Palm, 2002) in particular constitute valuable alternatives to evaluate sampling strategies, but their application in coral reefs is only recent (Ryan, 2004).

In the context of research programs recently initiated in New Caledonia on invertebrates ecology, an important precursor to addressing the question of species/habitat associations was the ability to accurately describe reef habitats, at relevant spatial scales (Dumas et al., 2007). The aim of this study was to develop and test a “quick and clean” photographic-based approach suitable for the accurate description of contrasted reef habitats. Photo transects were thus conducted by snorkeling in contrasted reef biotopes (reef flat, reef crest, sandy bottom) from the south-west lagoon of New Caledonia. Habitats were characterized from percent covers of 15 habitat categories (including sediment characteristics and reef structuring species), using computer-assisted point count methods. Using bootstrap resampling techniques, we statistically addressed the following questions: i) what is the influence of image processing (in terms of number of points analyzed per picture) on the accuracy of the resulting habitat description?; ii) what is the associated precision/variability?; and iii) what is the optimal processing strategy to provide “quick and clean” –i.e. statistically accurate and cost-effective– description of our reef biotopes?

2. Material & Methods

2.1. Study design

The study was undertaken in shallow fringing reefs of the south-western lagoon of New Caledonia. In the area, fringing reefs are generally composed of three successive zones: 1) a reef flat with poor coral cover; 2) a reef crest with flourishing coral cover; and 3) a slight slope connecting to the sandy bottom (Bozec et al., 2005). Photographic surveys were conducted in the latter habitats in February 2007 at 3 contrasted sites around Maître islet, Ngé islet and Larégnère reef (Table 1).

For each site, four randomly located (20×1 m) transects lines were selected. They were materialized by a color-marked survey tape attached to the substrate. Distance between the four transects was at least 10 m. Pictures were taken from the surface using a standard digital Canon S80 camera in Canon WP-DC1 underwater housing, so as to cover the entire transect area. High-quality pictures delivered by this 8 Mpixels camera are 3264×2448 pixels in size. As frame area differed between transects in relation to depth, a 1 m^2 graduated quadrat frame was successively moved along the line to help delineate the frame surface captured by the camera. For each picture, the photographer stationed above the quadrat, using the LCD screen before shooting to ensure that the camera was perpendicular to the substrate, so as to avoid image distortion. The optical zoom was used to counter-balance the effects of depth on the picture frame, by zooming in on the quadrat.

Table 1
Characteristics of the selected sites in the southwest lagoon, New Caledonia

Habitat	Location	Type	Coral cover	Exposure	Depth
1	Ngé islet	Reef crest	high	leeward	2.00–3.50 m
2	Larégnère reef	Reef flat	poor	windward	1.50–2.50 m
3	Maître islet	Seagrass bed	~absent	leeward	3.00–4.00 m

Table 2
Habitat variables used for habitat characterization in the selected sites, southwest lagoon

Sediment type	Substrate coverage
Mud	Massive corals
Sand	Digitate corals
Debris (1-5 cm)	Tabular corals
Boulders (<100 cm)	Soft corals (Alcyonarians)
Bedrock	Branching corals
Dead Coral substrate	Foliose corals
	Encrusting corals
	Seagrass
	Macroalgae

2.2. Image processing

At the office, digital pictures were imported and cropped within Adobe Photoshop prior to analysis, in order to provide 20 (1 m^2 equivalent) non-overlapping frames per transect. Picture sets were subsequently imported in an image analysis software including efficient, user-friendly features for the estimation of sediment and substrate cover using a) random point counts and b) image area analysis (CPCe “Coral Point Count with Excel extensions” software, Kohler and Gill, 2006). Fifteen categories of local habitat variables were considered, from previous results on invertebrates/habitat associations in Caledonian reefs (Dumas et al., 2007). The selected variables were related to sediment type (6 categories from mud to hard bottoms) and substrate coverage (9 categories for coral lifeforms, algae and seagrass) (Table 2).

For each transect, a reference habitat profile was calculated based on an exhaustive surface analysis. First, images were calibrated within the software using the graduated quadrat as a reference. Areas corresponding to habitat categories were then visually identified and precisely delineated using the software on each 1 m^2 image, and corresponding surfaces were computed. The overall surface per category was then summed over the 20 images, and transformed in percent cover per category to provide a reference profile for the whole transect. Data were then averaged by site.

In a second step, we used computer-assisted random point counts methods to subsample the previous picture sets. Data points were randomly selected and overlaid onto the pictures using the software, then habitat profiles were calculated from this limited set of points. In order to investigate the influence of the number of points analyzed per picture on the estimated percent covers, randomized replicates of habitat profiles were generated. First, each image was sub-divided into a 3×3 grid of 9 cells, with 11 random points per cell. This stratified random sampling procedure ensures that some points are sampled in each region of the image (Kohler and Gill, 2006), with a maximum number of 99 points analyzed per picture. Habitat categories were identified for the latter 99 points/image×20 images/transect, i.e. 1980 points per transect. Second, these 99 points were resampled using a bootstrap procedure: for each image, n points per cell ($1 \le n \le 11$) were randomly selected in the matrix from the 11 previously identified, i.e. $k=9n$ points per image ($9 \le k \le 99$) were sampled. For each transect, percent cover per habitat category were calculated at transect scale from the selected points over the 20 images, i.e. from the (9n×20) point data set. The operation was performed 1000 times for each value of k and each transect, thus resulting in 1000 randomized replicates per transect for all values of ($k=9n$, $n=1,..., 11$).

2.3. Data analysis

For reference profiles, Shannon-Weaver diversity index H' (Shannon and Weaver, 1963) was computed from habitat variables as a proxy for spatial diversity of habitats, i.e. to encompass the number of categories as well as their relative frequency distribution in the transects. Between-site differences in habitat richness (i.e. number of habitat categories) and diversity (H') were investigated using one-way factorial analyses of variance (ANOVAs).

Bootstrap estimates of percent cover per category were obtained by averaging bootstrap samples:

$$\hat{S}^{*}_{i,k} = \frac{1}{1000}\sum_{b} S_{i,k,b},$$

where i is a category, k is the number of points sampled per image, and b indexes the bootstrap sample.

We could then compare reference profiles and estimates derived from the point count subsampling method:

a) the accuracy of an estimation method quantifies *the average closeness of the estimator to its true value*" (Sokal and Rohlf, 1981). Conversely, the bias quantifies the discrepancy between the estimated value and the true, generally unknown value. For each transect, bootstrap estimates of bias were computed per habitat category as the difference between the reference percent cover S_i^{ref} and $\hat{S}^{*}_{i,k}$:

$$Bias\left(\hat{S}_{i,k}\right) = \hat{S}^{*}_{i,k} - S_i^{ref}$$

b) the precision of an estimator quantifies the *closeness of repeated measurements of the same quantity*" (Sokal and Rohlf, *op. cit.*). Conversely, the variance of an estimator quantifies the average dispersion of repeated estimates around their mean value. For each transect and each habitat category, bootstrap estimates of variance were computed per category as the unbiased estimate of the empirical variance of the bootstrap values $\hat{S}^{*}_{i,k}$:

$$\hat{V}\left(\hat{S}^{*}_{i,k}\right) = \frac{1}{999}\sum_{b}\left(S_{i,k,b} - \hat{S}^{*}_{i,k}\right)^2$$

c) upper limits of the 95% confidence interval of the bias estimates were calculated to provide statistical estimates of the "maximal

Table 3
Characteristics of the shallow, fringing reef habitats

	Habitat 1	Habitat 2	Habitat 3	*effect*
% live coral	73.08	15.01	2.80	***
Richness	10.2	8.2	9	N.S.
Diversity	2.31	1.53	1.44	**

Means per habitat for percent live coral, habitat richness (number of habitat categories), habitat diversity (Shannon H'). Factorial ANOVAs for habitat effect with associated level of significance: *p<0.05; **p<0.01; ***p<0.001).

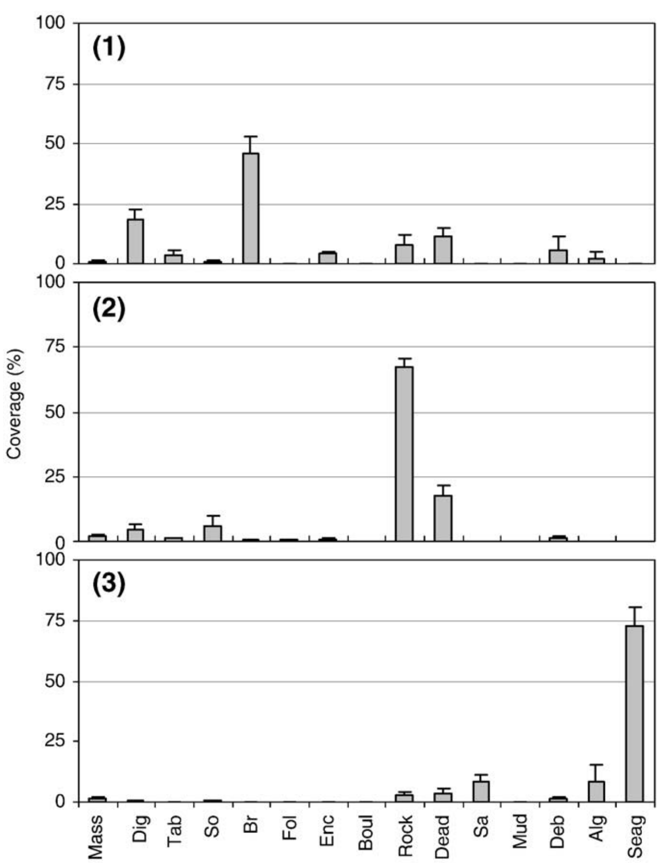

Fig. 1. Habitat profiles from the 15 local substrate categories in the 3 sampled sites (means and standard errors). 1, 2, 3: Reef crest, reef flat, seagrass bed, respectively.

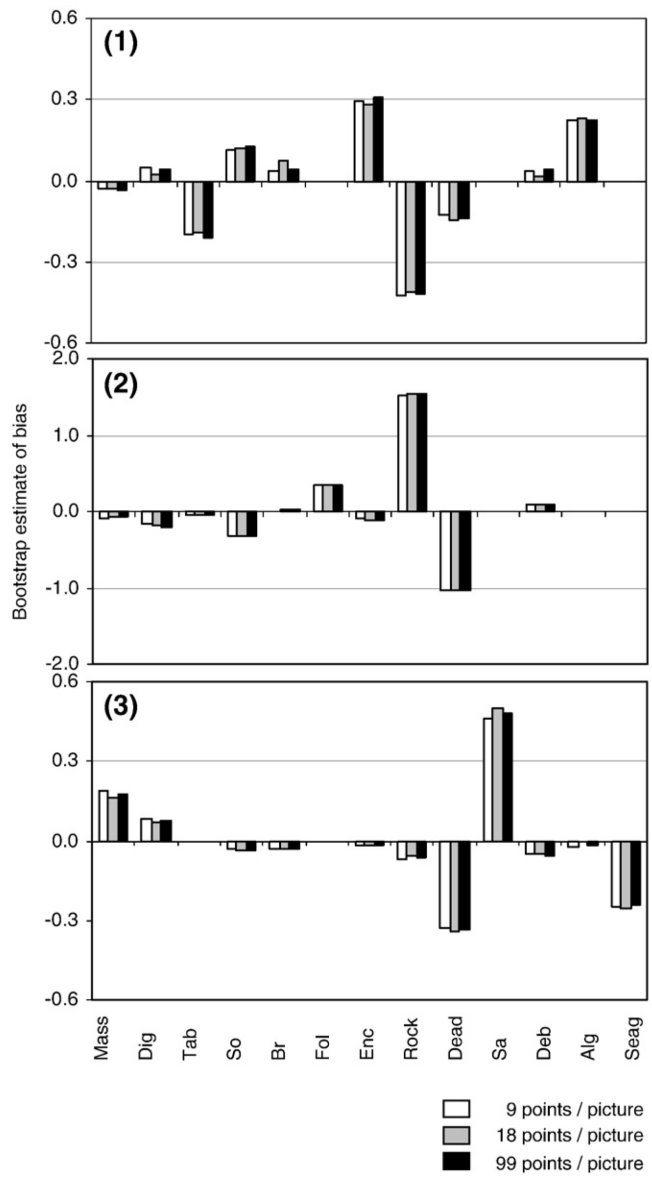

Fig. 2. Accuracy of point count estimates in the 3 sampled reef habitats. Bootstrap estimates of bias for 9, 18 and 99 points/picture. 1, 2, 3: Reef crest, reef flat, seagrass bed, respectively.

bias" that can be expected by the method. These values were computed per habitat category as a function of k, using Student's approximation for 95% confidence intervals (Scherrer, 1984):

$$MaxError_{95\%}\left(\hat{S}^{*}_{i,k}\right) = 2.306\sqrt{\hat{V}\left(\hat{S}^{*}_{i,k}\right)/4}$$

Results were then expressed as a percent of the reference cover values, providing estimates of "maximal error" in % for the different habitat categories and number of points analyzed per m^2.

3. Results

3.1. Habitat structure

Contrasted differences in substrate type and cover were observed between the three habitats (Fig. 1). Living corals strongly dominated in habitat 1 (reef crest, 73.1% of living corals), in particular branching/digitate corals (percent coverage 45.5%/18.3%, respectively). Habitat 2 (reef flat) was characterized by large-sized, hard rocky bottoms (67%) exhibiting sparse patches of both dead (17.7%) and living corals (15%). Habitat 3 was widely dominated by seagrass (>70%) lying on a sandy substrate, with very rare living coral colonies (percent cover <5%). Strong spatial homogeneity was observed within habitats, with low inter-transects variability for substrate/coverage variables.

No significant differences in richness (i.e. number of habitat categories) were observed between sites (mean 9.1 categories per site, N.S. ANOVA). Shannon-Weaver H' highlighted contrasted patterns between habitats ($p<0.005$, ANOVA), with decreasing values emphasizing decreasing spatial diversity from habitat 1 (reef crest) to habitat 3 (seagrass beds) (Table 3).

3.2. Efficiency of point counts method

3.2.1. Bias

Bootstrap estimates of bias displayed little differences between reference profiles and profiles obtained from point counts, whatever the habitat categories considered (Fig. 2): values generally ranged between -0.5 and 0.5 percent cover, with the exception of habitat 2 where differences were slightly higher (reef flat, maximum differences: -1.05/1.54 percent cover for dead coral/rock categories, respectively). In proportion, the largest differences occurred for rare habitat variables with low percent covers (<1%). No systematic trends towards over-/underestimation were observed for abiotic as well as biotic substrate cover variables.

Increasing the number of points analyzed per image from 9 to 99 had no significant influence on bias estimates for neither of the three sites (ANOVAs, N.S. for reef crest/reef slope/seagrass beds, whatever the variable considered): in all cases, the method provided estimates of percent covers very close to the reference values.

3.2.2. Precision

Bootstrap estimates of variance for replicates derived from point counts emphasized decreasing variability when increasing the number of points analyzed per image (Fig. 3). While similar patterns were observed for all the habitat categories considered, values computed from the 1000 randomized replicates per transect were extremely low, with variance always <0.001 in the three habitats whatever the number of points analyzed per image (maximum variance of 0.00055/0.00052/0.00046 for $k=9$ points/image in reef crest/reef flat/seagrass beds, respectively). Although increasing the number of points resulted in increased precision, in all cases the method provided extremely robust descriptions of the reef habitats.

3.2.3. Maximum errors

Similarly, maximal relative errors (i.e. the maximal differences between reference and point-counts derived values with 95% confidence

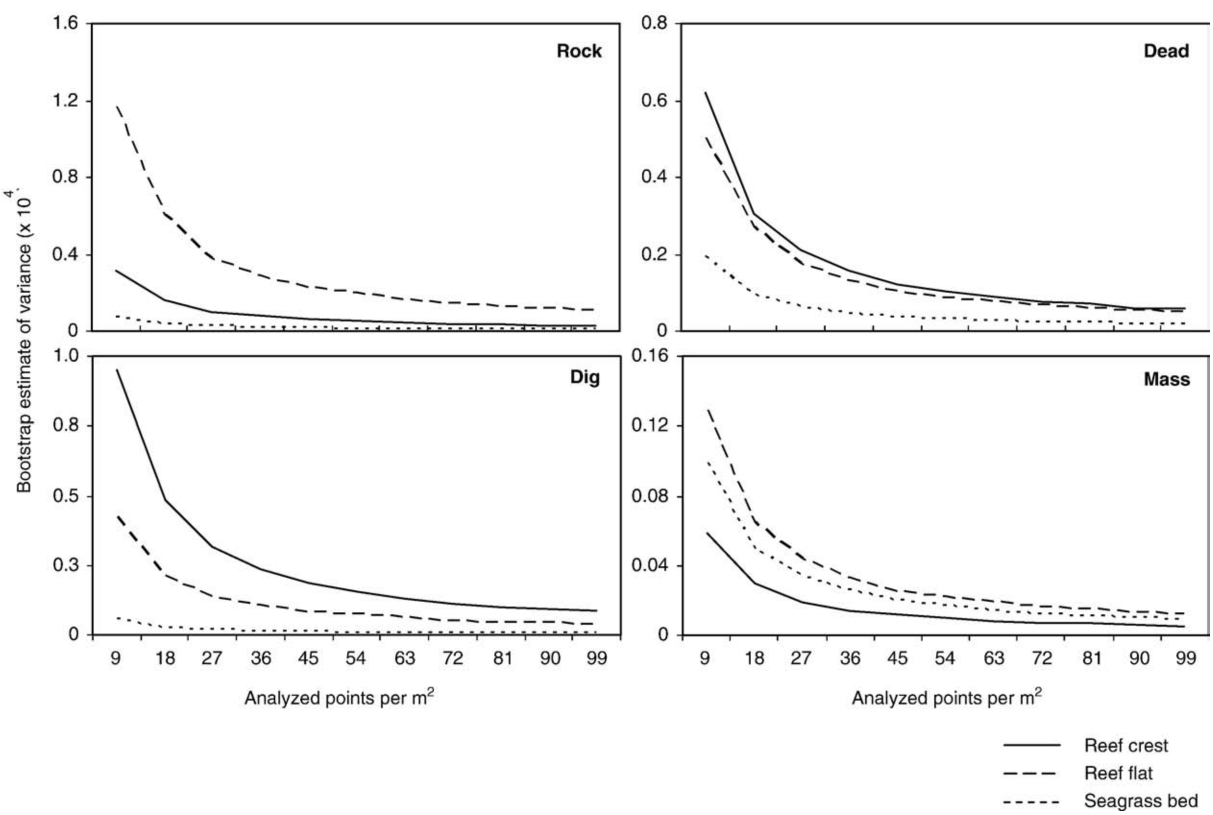

Fig. 3. Precision of point count estimates in the 3 sampled reef habitats. Bootstrap estimates of variance for 9-99 points/picture.

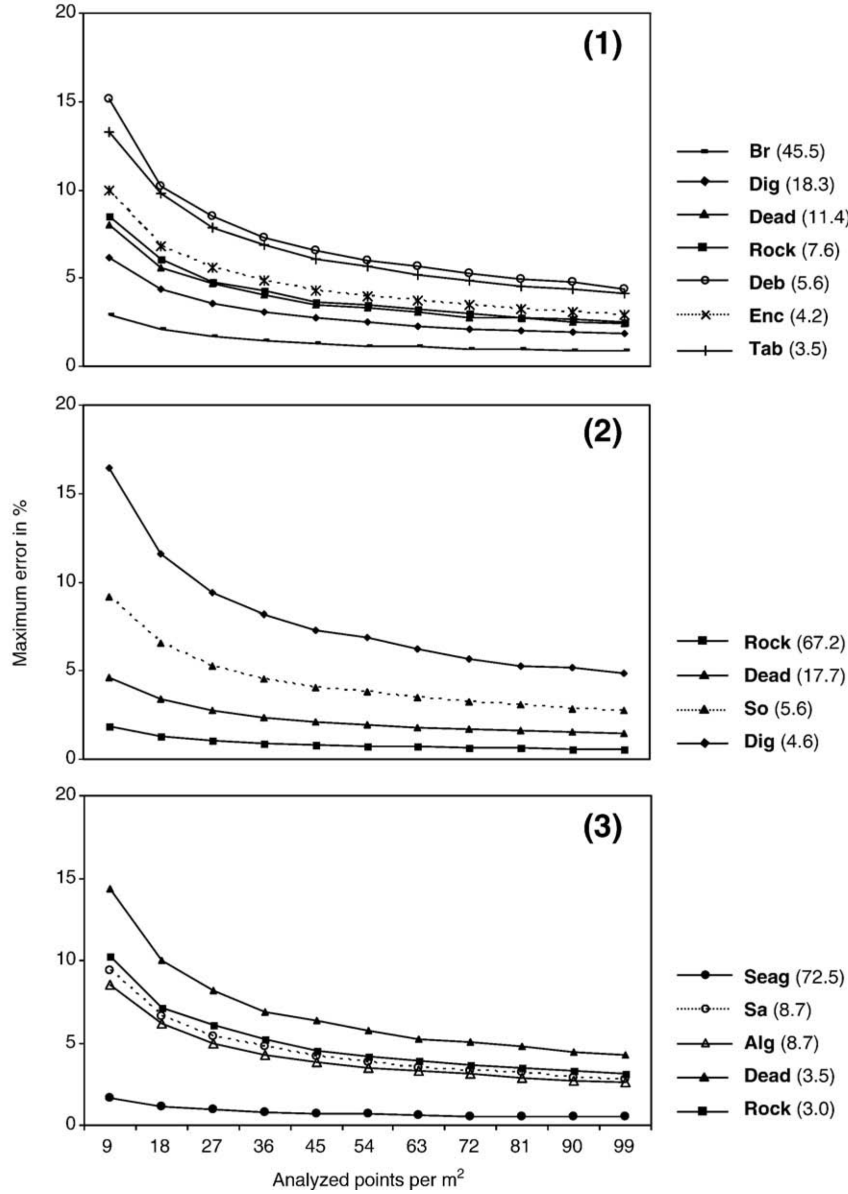

Fig. 4. Maximum relative errors (in %) for point count estimates in the 3 sampled reef habitats. Error expressed in percent of the reference values for categories ≥3 percent cover (reference values given between brackets). 1, 2, 3: Reef crest, reef flat, seagrass bed, respectively.

level, expressed in % of the reference value) consistently decreased when the number of points analyzed per image increased. Our results emphasized consistent patterns across the three different habitats: while dominant categories exhibited low error values with small range of variation (e.g. maximum errors ranging from 0.5% to 2.9% for categories >45 percent cover, for k between 9 and 99), increasing the number of points had strong impacts for rare/very rare habitat categories (cf. Fig. 4). For the latter, the high relative errors generally observed highlighted that description was less reliable, especially at low k values: very rare categories with percent cover <1 thus exhibited maximum error ranging from 23% to 90% for k=9/12% to 40% for k=45/7% to 28% for k=99.

4. Discussion

4.1. Photographic interpretation of habitat

Addressing the issue of interpreting complex habitat structures is a main concern for coral reef ecologists: as virtually all the techniques commonly used for habitat description rely on 2D projections obtained within a 3D environment, systematic biases that are difficult to correct are likely to affect surface estimates (Porter and Meier, 1992). Despite methods were specifically developed to estimate 3D reef surfaces, either directly in the field (e.g. wrapping techniques with different materials, see Alcala and Vogt, 1997) of from computed 2D/3D conversion indices (Chancerelle, 2000), methodological/logistical issues generally prevent them to be used for routine surveys. In practice, reef habitats are most commonly characterized from quantitative estimates of percent cover for a selection of reef-structuring elements (sediment, corals, macrophytes, algae etc.) using simple planar, vertical projections (Chancerelle, 2000).

In this framework, photographic methods provide simple, low-expensive approaches yielding high quality information on benthic communities, including species abundance/diversity, size, and, in some cases, recruitment, growth and mortality (see English et al., 1997; Hill and Wilkinson, 2004). Percent covers can be easily derived from pictures using either area analysis or point count methods. Although area analysis is potentially the most accurate and precise method (i.e. providing the best proxy of reef habitats), it is also the most time-consuming method, therefore it is not usually considered in comparative studies addressing benthic surveys. In this study, we used exhaustive area analyses to provide reference surface values being as close as possible to the "real world": each square meter of the 240 m^2 area considered in this study (i.e. 4 transects × 3 habitats × 20 m^2/transect) was captured using high resolution photography and entirely analyzed using computer-assisted manual digitalizing of all habitat features. While the process was highly time-consuming, the resulting percent cover were considered reliable baseline values for subsequent comparisons with surface estimates derived from contrasted point count strategies.

4.2. Reef habitat structure

According to previsions, strong, overall homogeneity was observed within the three sites that were selected to constitute "archetypes" of Caledonian shallow fringing reefs habitats. The distribution of variables relative to sediment composition and coverage by living species emphasized the expected trends for reef crest, reef slope and soft bottom: reef crest habitats in the wave-protected, leeward zone of Ngé islet exhibited flourishing, quasi-continuous coral cover (living corals >70%, living + dead corals >80%) with high structural diversity relying on the presence of diverse life forms categories (digitate, tabular, massive, foliose, encrusting, soft corals). Reef flats on exposed, windward zones of Larégnère reef had intermediate structural diversity, with patchy distribution of corals (15% living/18% dead) lying on eroded, rocky substrate. Deeper, sandy bottoms on the leeward side of Maitre islet were extensively covered by sea grass (>70%), although algae and corals punctually occurred in small patches. Combining the number of categories observed per reef habitat and their relative distributions through Shannon-Weaver' H' also yielded interesting insights on habitat structure: while formally addressing the question of habitat diversity in coral reef is beyond the scope of this study, results highlighted that our intuitive grasp of "diversity" appeared more strongly related to the relative distribution patterns of reef-structuring elements than to their absolute richness. Despite all habitats exhibited similar numbers of sediment/associated species categories (9 ± 1), seagrass habitats with strongly unbalanced distributions (dominant category = 72.5% of surface cover) were initially considered simple, quasi-uniform biotopes compared to reef flats (dominant category = 67.2%) then reef crests (dominant category = 45.5%). While focusing on small-scale structural diversity is probably not relevant for management-oriented monitoring surveys, the "descriptive resolution" (*sensu* Mumby, 2001) of methods used for characterization of reef habitats may thus constitute a key issue when working in ecologically-oriented, research perspectives.

4.3. Efficiency of the method

In marine or terrestrial ecosystems, point intercept techniques (Pielou, 1974) are widely used to increase the efficiency of habitat surveys, by speeding up the process of estimating quantitative surfaces from image recordings. Contrasted strategies can be found in the literature in terms of point allocation (random, semi-stratified, stratified etc.) and number of points per frame, as a consequence of trade-offs between the level of accuracy/precision needed and the amount of time required for image processing. In coral reefs, the efficiency of point counts-based methods is generally addressed from restricted (field) data sets, which raises statistical issues to provide estimates of accuracy and precision (Ryan, 2004) and adapt sampling protocols accordingly. In this study, the effects of increasing the number of points analyzed per frame were assessed using nonparametric resampling techniques that are particularly appropriate for ecological data. These sampling-based randomization techniques provided robust, reliable statistical estimates in contrasted habitats for numbers of points comprised between 1 and 99 per frame.

Our results emphasized low bias and high precision for percent cover estimates derived from point counts, for all the 15 considered habitat categories: maximum deviations from reference values were ~1 percent cover in almost all cases, and were very stable between replicates whatever the reef biotopes considered (reef crest, reef flat, sandy bottom, variances <0.001). No systematic trends in underestimating or overestimating percent covers were detected.

On the whole, the method clearly provided reliable, quantitative descriptions of our reef transects, especially for well-represented habitat categories. It should be noticed that reliability of point count estimates mainly differed as a function of spatial coverage. From a practical point of view, increasing the number of points analyzed from 9 to 99 per image did not really change the global efficiency of the method for dominant habitat categories: no significant increase was observed for accuracy, gains in terms of absolute precision were extremely low, while time required for transect image analyses dramatically increased. While rare categories (i.e. with percent cover <5%) were still detected using point counts, they exhibited high relative errors in comparison with major categories, in particular when using low number of points per m^2. In seagrass beds for example, maximal error estimates for the dominant category (sea grass, 72.5% of surface cover) using 9 points/m^2 were 1.2 percent cover, yielding a low 1.6% relative error. In the same habitat, error estimates for rare coral categories (e.g. rock, 3% of habitat surface) provided a 10% relative error. For very rare categories (<1%), detection was hazardous and the associated error levels dramatically increased. In the latter cases, increasing the number of points can achieve acceptable error levels, but with considerable increase in processing time.

Habitat diversity (in terms of relative distribution of reef-structuring elements) may thus partly influence the outcome of the method, at least for very low represented categories (which are usually not detected using standard transect methods such as LIT/PIT, Hill and Wilkinson, 2004). While our categories of interest were initially selected within the perspective of matching scale-/species specific questions, results may also differ when considering alternate habitat variable classification (e.g. requiring high taxonomic resolution for corals rather than life forms). The choice of a restricted number of sites may also be a concern for large-scale validation of our results, as they cannot be considered representative of all potential diversity patterns encountered in coral reefs. Yet, as very high statistical efficiency was observed in these contrasted, "archetypal" reef situations, and keeping in mind that every method has intrinsic limitations, we advocate that conclusions are likely to be generalized to the majority of coral reef conditions.

4.4. Photographic vs. video techniques

While in the recent literature, high-resolution photography is mainly devoted to small-scale approaches, reef surveys at spatial scales comparable to the present study (i.e. meso-scale or larger) are mostly based upon scuba-based video techniques (Carleton and Done, 1995; English et al., 1997; Page et al., 2001; Hill and Wilkinson, 2004; Brown et al., 2004; Jokiel et al., 2005). Rationales for this mainly rely on equipment/field constraints, as these methods allow easier captures of large reef areas per unit of diving time when using scuba equipment. Yet, video recordings exhibit much lower resolution/image quality compared to still photography that may not allow easy habitat description unless the diver stays close to the substrate, even for the most recent underwater high-definition cameras (Lam et al., 2006). In contrast, the high quality pictures delivered by our standard 8 Mp digital camera allowed us to identify habitat features on images taken from the surface, up to 4.50 m above the substrate. Maximum depths will actually vary depending upon camera features and geographical, local environmental factors (e.g. turbidity), but preliminary tests in our stations provided usable pictures over a 0.5-6 m depth range. As the substrate area captured per frame is directly related to depth, large transect width can be captured on a single swim compared to videotaping: our camera with standard 28 mm-equiv. focal length thus captured 0.75 m^2 substrate area per picture in 1 m depth/2.4 m^2 in 2 m depth, when the optical zoom was not used. In comparison, video transects are usually recorded 0.5-1 m above the seabed, i.e. with equivalent substrate area <0.5 m^2 per extracted frame and therefore require multiple transect swims to provide equivalent area coverage. Drawbacks of variable transect widths can be easily overcome in the case of high resolution pictures, using the graduated survey tape to perform *a posteriori* image scaling for area standardization.

4.5. Guidelines for a "quick and clean" photographic-based description of reef habitats

As a consequence of technological innovation, considerable effort has been devoted in the recent years in developing/testing new methods for monitoring coral reefs. Proliferation of specific equipment-based techniques thus complicate matters, comparative studies still being in their early stages for photo/video methods. Efficiency of point counts is usually expressed in terms of points per frame, but highly variable frame areas are considered in the literature for photo/video methods with respect to camera characteristics, height from substrate, diving equipment, time required etc.: 0.075 to 0.5 m^2 (Brown et al., 2004), 0.06 m^2 (Ryan, 2004), 0.15 to 0.26 m^2 (Lam et al., 2006), 0.34 to 1 m^2 (Jokiel et al., 2005), among others. A first, simple step towards standardization could be the achieved by i) systematically providing estimates of the substrate area captured from still pictures/video-extraction (which is not always the case), and ii) relating sampling effort (e.g. point counts) and subsequent efficiency measures to the latter surfaces.

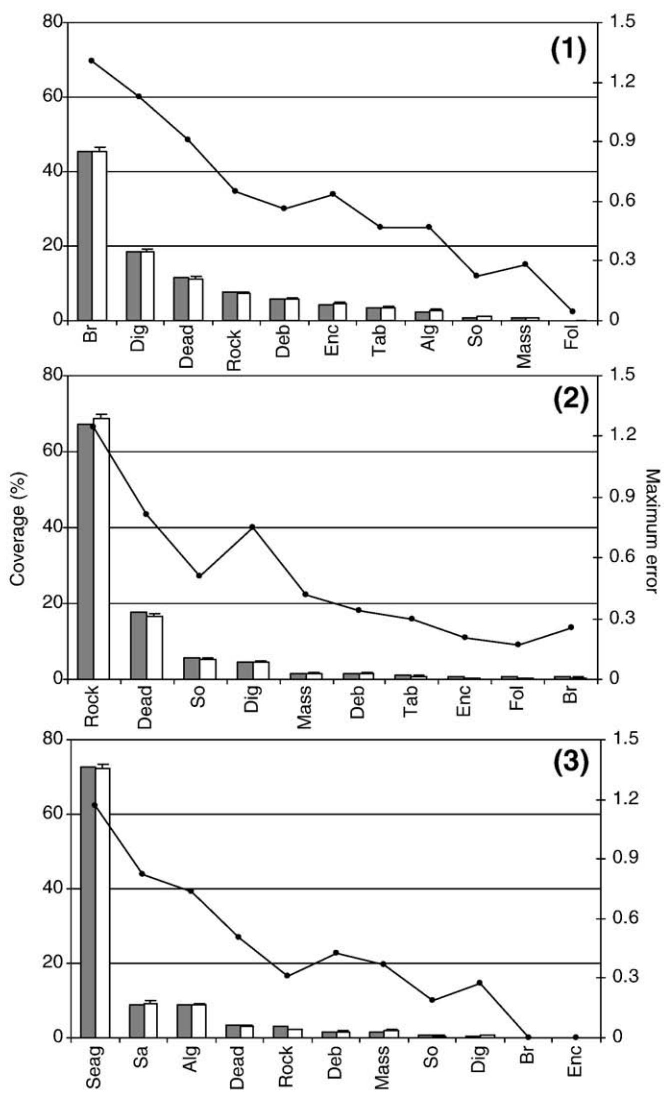

Fig. 5. Recapitulative summary of method' efficiency for the recommended 9 points/m^2 ratio. Reference and estimates of percent covers for the 15 habitat categories in the sampled reef habitats (means with standard deviations) and associated maximum errors. 1, 2, 3: Reef crest, reef flat, seagrass bed, respectively.

Table 4
Summary: minimum requirements for the surface-based photographic method, using a 9 points/m^2 ratio

Minimum requirements	Field	Laboratory
Personnel		
Number	1 snorkeller$^{(1)}$	1
Field of expertise	Photography	Habitat identification
Expertise level	Middle	Advanced
Equipment	Snorkelling equipment	
	Survey tape	Computer
	Digital camera	CPCe software
	Underwater housing	
Time		
Data collection	2-4 minutes$^{(2)}$	-
Data analysis	-	10-20 minutes

$^{(1)}$under sufficient safety considerations.
$^{(2)}$not including optional survey tape operations (approx. 5 minutes).

From our results, and keeping in minds the limitations of the method (in particular for low-represented habitat categories), using high resolution pictures with 9 points analyzed per m^2 could be considered the optimal strategy to provide reliable, cost-effective description of coral reef shallow habitats at the scale considered in this study (cf. synthesis on Fig. 5). The 9 points/m^2 ratio therefore constitutes a simple, convenient guideline that allows flexible implementation of the method whatever the equipments, depth conditions or images considered – provided that image quality is sufficient for habitat identification, and image scaling can be performed to adjust the number of points overlaid. This is of particular interest as variable transect widths are usually found in the literature, depending upon the spatial distribution scale of the investigated processes/species (e.g. Hill and Wilkinson, 2004). Preliminary tests advocate that moderate increase in transect width (i.e. up to 3 m) should not strongly affect neither accuracy nor precision of the method (P. Dumas, unpublished data). Yet, further work will be required to formally test this hypothesis, in particular in complex habitats where longer/wider transects may encompass more spatial heterogeneity and thus reduce the ability to detect patchy, rare reef-structuring elements (Brown et al., 2004).

Minimum requirements in terms of personnel/equipment/time are summarized in Table 4. While this method does not require diving equipment (picture are captured from the surface) and could be easily conducted by a single snorkeller under sufficient safety considerations, the presence of a second snorkeller or diver in charge of the survey tape can strongly ease field operations. In the latter case, it took us 15-30 minute per transect for the entire process, from field data collection to computation of final percent covers. Field operations were short in time (<10 minutes, including survey tape roll out/in and image captures), with main differences relating to laboratory processing time (10-20 minutes per transect, in relation with habitat diversity and picture quality). The field process can also be simplified for experienced photographers, who may not need the assistance of the optional 1 m^2 quadrat for framing. In this case, image calibration can be similarly performed in CPCe using the photographed survey tape (instead of the graduated quadrat frame) as a reference.

The proposed method relies on the assumption that benthic habitat categories can be readily distinguished on the captured images. As better image quality enhances substrate identification and image processing, particular attention should be paid to avoid motion blur, especially in low-light/wavy conditions. Best results are generally obtained using semi-automatic camera settings, with shutter speed/

aperture/sensibility parameters set to ensure high depth of field/shutter speed. Yet, given the recent advances in digital photography, this shallow waters surface-based approach does not suffer intrinsic limitation in terms of precision or scales that could not be technically overcome by the use of relevant technical choices (camera/image resolution, lens focal length/aperture, etc.).

As it was prophesized ~30 years ago by Drew (1977), advances in technologies and equipment considerably expanded our ability to effectively describe coral reef habitats. As the "health" of coral reefs is more than ever a topical question, digital-picture based surveys (photo/video) constitute recent cost-effective, powerful approaches to document ecological changes over a wide range of scales. The surface-based photographic method outlined in this paper was developed to combine high statistical efficiency and logistical ease, i.e. to provide a flexible "quick and clean" method for fine-scale description of coral reef habitats. Now that this initial step is achieved in New Caledonia, it will allow further work to address more functional perspectives, e.g. fine-scale species/habitat patterns and processes.

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