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Characterizing the diversity of coral reef habitats and fish communities found in a UNESCO World Heritage Site: The strategy developed for Lagoons of New Caledonia

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ABSTRACT

Since 1972, the UNESCO "World Heritage Convention" offers an international canvas for conservation and management that targets areas of high cultural and environmental significance. To support the designation of areas within the 36.000 km^2 of New Caledonia coral reefs and lagoons as a World Heritage Site, the natural value and diversity of the proposed zones needed to be demonstrated. To exhaustively identify each configuration of shallow habitats, high resolution remote sensing images were used to select the sampling sites. This optimal scheme resulted in the selection of nearly 1300 sampling sites, and was then simplified to render its application realistic. In the final sampling plan, only the most common or the most remarkable coral zones were selected. Following this selection, *in situ* habitat and fish surveys were conducted in 2006–2008 in five large areas spanning a 600 km-long latitudinal gradient. Habitats were described using line-intercept transects in parallel with underwater visual census of indicator and commercial coral reef fish species. We report here on the results achieved in terms of: (i) the actual diversity of coral habitats captured by the remote sensing based sampling strategy, (ii) the different reef fish communities captured from the different sites, and (iii) how well they represent New Caledonia diversity. We discuss the possible generalization of this scheme to other sites, in the context of World Heritage Site selection and for other large-scale conservation planning activities.

1. Introduction

Since 1972, the UNESCO "World Heritage Convention" offers an international, highly visible, prestigious canvas for conservation and management that targets areas of high cultural and environmental significances. Despite the inclusion of the entire Great Barrier Reef in Australia, and several other much smaller locations worldwide on the World Heritage List, coral reefs remain poorly represented. After more than two years of preparation and review, in July 2008, several coral reef areas of New Caledonia were designated for their high environmental value (World Heritage Committee, 2008).

To support the designation of areas within 36.000 km^2 of New Caledonia coral reefs and lagoons as a World Heritage Site, it was first necessary to demonstrate the natural value and diversity of the proposed zones. Given the size of the considered domain, no historical or recent data on habitats, benthic or pelagic communities existed consistently for the entire domain. The only data exhaustively covering all of New Caledonia's reefs were remote sensing images and geomorphological map products from the Millennium Coral Reef Mapping Project (MCRMP), a project that systematically mapped coral reefs worldwide since 2004 (Andréfouët et al., 2006). Using the MCRMP maps and also taking into account several criteria defined by UNESCO (e.g. absence of mining in the proposed sites), the New Caledonia Committee in charge of the case selected six candidate 'clusters' of various sizes and complexities (Fig. 1). The proposed clusters (Ouvéa-Beautemps-Beaupré, Récifs d'Entrecasteaux, Zone Côtière Ouest, Grand Lagon Sud, Grand Lagon Nord, Zone Côtière Nord Est) included all the major geomorphological complexes found in New Caledonia according to the MCRMP (Andréfouët et al., 2007). Given the extent of the proposed clusters and the high diversity of reef structures included, it was assumed that significant diversity of habitats and species would be included. However, the exact diversity of habitats and communities needed to be assessed consistently for all clusters since recent coral reef research, surveys and on-going activities had focused on limited areas only (e.g. McKenna et al., 2006; Mellin et al., 2007; Mattio et al., 2008; Wantiez, 2008). Although the status of New Caledonia's reefs has been monitored yearly since 2003 on 30 permanent selected stations (Wantiez, 2008),

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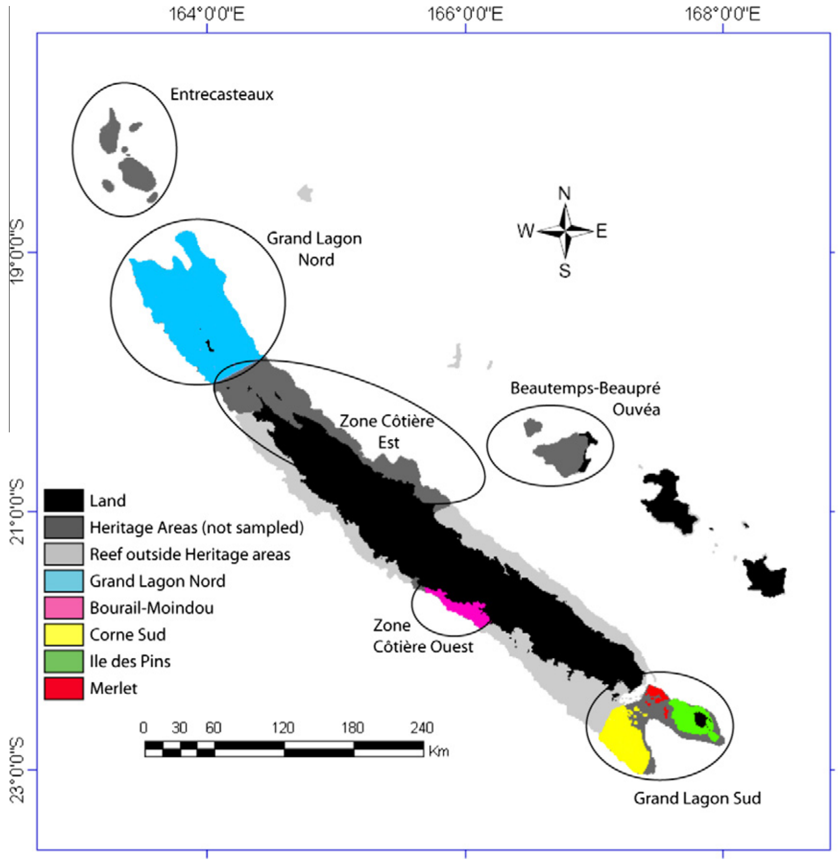

Fig. 1. Map of New Caledonia with the six different clusters (noted in black circles) now designated as a UNESCO World Heritage Site (lagoons of New Caledonia: Reef Diversity and Associated Ecosystems), and in color the five different areas sampled for this study.

most of these stations are outside of the limits of the proposed clusters. Relying on only 30 sites was deemed insufficient to build the UNESCO case.

As data regarding New Caledonia's reefs were needed within one year, it was decided to couple the exhaustive synoptic view provided by remote sensing with traditional field survey techniques used to describe habitats and fish communities. We report here on the principles and techniques applied to select representative sampling sites throughout New Caledonia, the type of surveys conducted for habitats and fish communities, and the results achieved in terms of (i) the actual diversity of coral habitats captured by this sampling strategy, and (ii) the reef fish communities captured from the different sites, and how well they represent New Caledonia's coastal marine diversity given existing knowledge. We believe the scheme applied in New Caledonia could serve as a guide for other countries and regions seeking to have their coral reefs designated as a UNESCO World Heritage Site. We discuss the possible generalization of this scheme to other sites, specifically in the context of UNESCO World Heritage Sites and also for large-scale conservation planning in general.

2. Material and methods

2.1. Identification and selection of habitat and fish sampling sites

The New Caledonia Committee in charge of the UNESCO case agreed with the suggestion to build a consistent sampling program for all clusters using satellite imagery as the primary source of information. The rationale was that a maximum of habitat diversity present in New Caledonia could be captured this way. Thus, sampling a maximum of habitat diversity was the primary retained criteria for site selection. Other criteria such as exposure to known disturbances (fishing, mining outside the selected areas, etc.) were not explicitly taken into account, but expected to be indirectly included if all habitats were integrated across the targeted clusters. This strategy was followed for mangroves, seagrasses, and coral habitats. However, we report here only on results obtained for coral habitats since mangrove and seagrass specific surveys were not performed. We formalized our approach through six working paradigms:

1. A reef is a spatial assemblage of habitats, that can be defined hierarchically, and identified with remote sensing images. The first coarse level of any habitat definition is geomorphological. Other finer levels account for benthic cover and architecture, and taxonomy of structuring species like coral, seagrass, and macroalgae;
2. A maximum number of MCRMP geomorphological classes (i.e. coarse habitats) needs to be included in the sampling design;
3. An optimal sampling scheme should allow for the monitoring of each type of habitats (exhaustivity criteria). Thus, each habitat should be included;
4. Sensitivity to perturbations is potentially different from one type of habitat to another. Thus, each habitat receives the same level of priority in the design;
5. The selected sampling sites must homogeneously cover all reef areas. Indeed, the same habitat found in two sides (e.g. North and South) of a UNESCO cluster could be subjected to different perturbations and evolve differently. Thus, the number of sites depends on the spatial distribution of the habitats, and may vary according to habitat type. For instance, forereef sites should be regularly spaced along the reefs, following changes

in exposure to waves' dominant direction. However, within each site, the number of transects and observations is the same and determined in advance by a power analysis with the adequate precision sought for habitat and fish data;

6. Since only raw remote sensing images (and not simplified habitat maps) can reveal the full diversity of reef habitat configurations, site selections were based on raw imagery photo-interpretation. Sites were thus limited to the 0–15 m depth range.

Practically, a first series of sampling sites was proposed based on the photo-interpretation of Landsat images, complemented in some areas by selected SPOT 5 and Quickbird images (Fig. 2). The spatial resolution of the images ranged from 2.4 m down to 30 m. The useful (i.e. within the blue–green–red wavelength optical range) spectral resolution ranged from 2 bands (SPOT 5) to 3 bands (Landsat, Quickbird). Photo-interpretation was made easier by our knowledge of New Caledonia reefs and by similar numerous sampling exercises conducted worldwide for habitat mapping whereby the selection of sites is based on a combined representativity/exhaustivity criteria (Andréfouët, 2008). The rationale for using raw imagery *vs* some form of pre-interpreted maps or unsupervised classification is explained in Andréfouët (2008).

The second phase is a simplification stage. The previous step implies that given the size of the targeted area, possibly thousands of sampling sites can be identified to respect the exhaustivity and spatial coverage constraints. Realistically, given the costs of a survey, it is necessary to scale down the survey to a manageable size. The benefit of the first exhaustive step is that a full reference is created against which the representativity of the actual survey can be tested. Simplifications can obey the following different criteria, applied in separate iterations:

1. *Representativity:* the most common configurations are prioritized, in order to use a limited number of habitats frequently found to assess and more easily detect future changes over/across the entire domain;

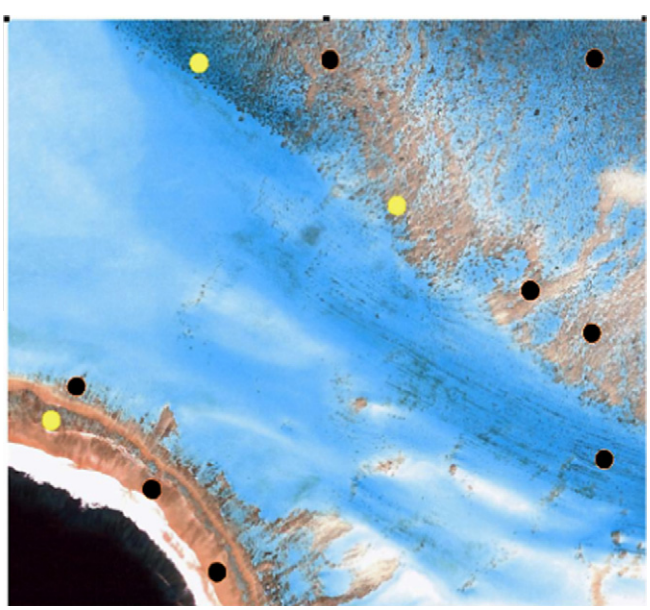

Fig. 2. Example of site selections using Quickbird images according to color-texture information. The scene includes a barrier reef and lagoonal patch reef area from a 1.5 × 1.5 km subset of the Moindou area, in the Zone Côtière Ouest cluster (Fig. 1). The optimal site selection scheme would include at least all black and yellow points to cover the different configurations of texture and color throughout the scene. After necessary simplification, only the yellow points would be conserved.

2. *Thematic exhaustivity:* at least one site for each habitat needs to be included;
3. *Rarity:* the rarest and most unusual configurations are prioritized;
4. *Spatial exhaustivity:* the spatial coverage needs to be as wide as possible;
5. *Thematic specificity:* priority is given to coral habitats likely to have high coral cover and rich coral communities;
6. Reef areas are prioritized over lagoonal areas.

In other words, the first simplifications proposed the minimum number of sites to spatially cover the different areas and have at least one site for each habitat, including rare ones. Then, final simplifications based on criteria 5 and 6 meant that the surveys would focus on coral rich habitats found on reef frameworks. This simplification stage needs to be repeated until the number of sites is compatible with the funds and time allocated for the surveys. Thus, different sampling schemes were iteratively created, from an "ideal" one down to a pragmatic one. The representativity of the later is known thanks to the former.

2.2. Habitat and fish survey protocols

Habitat and fish communities were sampled *in situ* in five large areas within three of the clusters included in the World Heritage List (Fig. 1): Corne Sud (15 stations; August 2006; 2–9 m depth), Ile des Pins (23 stations; October 2006; 2–9 m depth), Zone Côtière Ouest (15 stations; April 2007; 1–7 m depth), Grand Lagon Nord (29 stations; December 2007; 1.5–9 m depth), and Réserve Merlet (21 stations; March 2008; 1–9 m depth). The dataset covers a 600 km-long latitudinal gradient, from the Grand Lagon Nord area (19°S) in the north down to the Corne Sud area (23°S) in the south. The Récif d'Entrecasteaux cluster (Fig. 1) was sampled in 2006, but data remain unavailable.

Habitats were characterized using the line-intercept transect (LIT) method modified by the Australian Institute of Marine Science (English et al., 1994). At each station, substrate categories were recorded along a 50 m transect laid perpendicularly to the slope (constant depth). Thirty detailed substrate categories belonging to 12 broader substrate categories were recorded. These were: branching, tabular, encrusting and foliose corals; submassive and digitate corals; massive and encrusting corals; soft corals; macroalgae and turf; other living animals; dead corals with algae; calcareous algae; sand; rubble; rock; crevasse. The percentage of each substrate category at each station was calculated by:

$$\%_i = 100\frac{L_i}{L_T}$$

where $\%_i$ is the percentage of substrate category i; L_i is the total length of category $i(m)$; and L_T is the total length of the transect (50 m). The habitat structure and variability was described using a cluster analysis (Ward agglomerative method) (Legendre and Legendre, 2000). Comparisons between groups were analyzed using Kruskal–Wallis tests.

Commercial fish species and indicator fish species found on a pre-established list of 311 species were recorded by visual census at each station, using a distance sampling method (Buckland et al., 2001; Kulbicki and Sarramégna, 1999). Two divers counted all fish by species along a 50 m transect, estimated their size (fork length) and their perpendicular distance to the transect. One diver counted the commercial species and the other the indicator species. Densities were estimated with a robust descriptor (Kulbicki and Sarramégna, 1999):

$$D = \frac{\sum_{i=1}^{p} n_i d_i^{-1}}{2L_T}$$

where D is the density (fish m^{-2}); n_i is the abundance of species i; d_i is the average distance of species i to the transect; p is the number of species; and L_T is the total length of the transect (50 m). The average distance of species i to the transect was calculated with:

$$d_i = \frac{1}{n_i}\sum_{j=1}^{o_i} n_j d_j$$

where o_i is the number of occurrences of species i; n_j is the number of fish of species i observed at occurrence j; d_j is the distance of fish of species i to the transect at occurrence j.

Fish assemblages and their links with habitat variables were identified using a canonical correspondence analysis (CCA) (Ter Braak, 1986). A permutation Monte Carlo test was used to select significant habitat variables. A cluster analysis (Ward agglomerative method) on the stations' scores on the four first axes extracted by the CCA was used to identify the different fish assemblages.

3. Results

3.1. Image interpretation, number of sites, and geomorphological representativity

Not surprisingly, between the three types of remote sensing images, the 2.4 m resolution Quickbird images were the most useful when available, since they provided detailed views of the different configurations of habitats based on color and texture (Fig. 2). Landsat data were the next most useful dataset, despite their lower spatial resolution. The presence of a blue band contributed greatly to revealing a high number of configurations that were poorly discriminated in SPOT 5 images (Fig. 3). Using Quickbird, instead of Landsat, where available, implied that more interesting sites worth including in the sampling could be detected since texture, color, and patchiness were better resolved. However, the different areas and clusters had their own specific configurations and complexities, and the sampling was not necessarily dependent only on sensor specifications. For instance, Grand Lagon Nord, which was studied with selected Quickbird data, was far less complex than Zone Côtière Ouest, but it was much wider. When available, using Quickbird images did not drastically change the number of sampling points for Grand Lagon Nord reefs when compared to a Landsat-based selection for the same reefs.

Initial site selection, prior to simplification, provided a total of 1290 sites for all Heritage clusters included. It is worth noting that this number represents approximately 1 site per km of linear reef. Thus, on average, it is not a tremendously high spatial sampling rate, even if the rates can be much higher on complicated areas (Fig. 4). After elimination of duplicates per habitats, the total number of sampling sites decreased to 591 sites; still an unrealistic number of sites to survey, with a number of sites ranging from 10 (Beautemps–Beaupré) to 203 (Grand Lagon Nord). Overall, the simplification yielded a loss of 1/3–1/2 of the initial number of sites per areas (Fig. 4), except for low complexity areas where the number of chosen sampling site remained close to the initial number. This scheme, deemed still too extensive in several areas, was simplified again due to logistical constraints for field surveys that limited the efforts to ~10–30 sites per week and per zone. Final sampling site decisions were based on criteria such as distance, protection, and navigation safety for each zone.

The level of inclusion of MCRMP classes was variable between areas. It is interesting to visualize MRCMP representation because it is the only habitat data, for New Caledonia, where explicit class definition and attributes could be provided before the surveys. Post-surveys information provided detailed habitat labels and attributes, but cannot be applied retroactively to all possible sites. MCRMP classes' occurrence thus provides information on the representativity of the selected sites for all of New Caledonia. At the

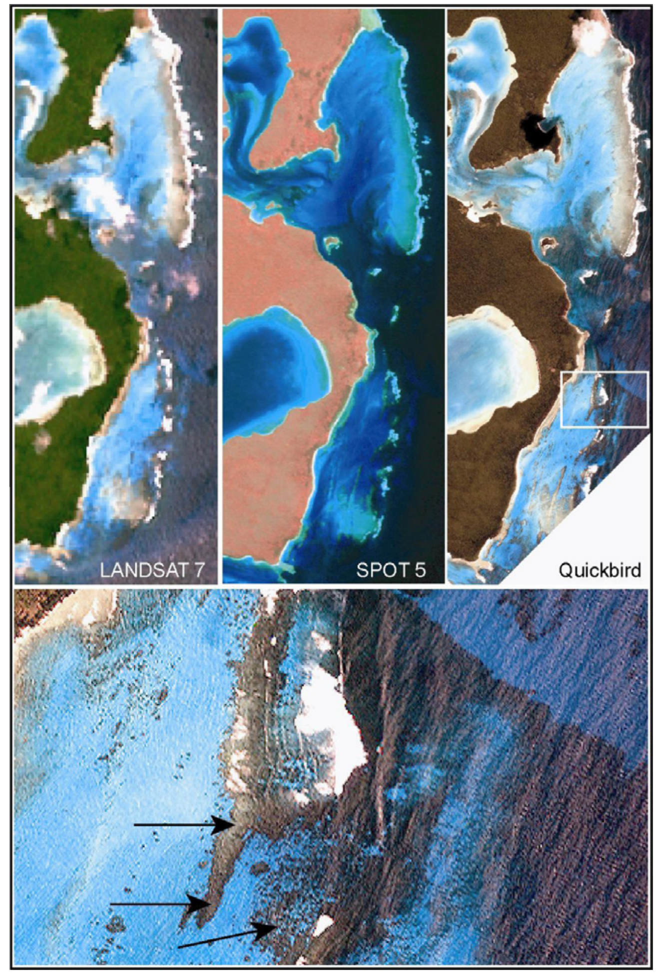

Fig. 3. Comparison of patterns visible on Landsat (R, G, B), SPOT 5 (NIR, R, G) and Quickbird (R, G, B bands), satellite images for the same area of Ile des Pins in the Grand Lagon Sud cluster ((Fig. 1). Quickbird data provide superior texture and color information due its spatial resolution and availability red, green, blue bands. The bottom panel depicts a close up of the area within the white box from the Quickbird image. Arrows point to different areas of a reef flat in color and texture that are likely different in benthic cover and architecture. The SPOT 5 image is the less informative due to its spectral resolution. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

most detailed geomorphological level, there are 152 Millennium classes in New Caledonia (Grande Terre and Loyalty Islands included, but without Chesterfield) (Andréfouët et al. 2006). In the six New Caledonia Heritage clusters (Fig. 1), 122 classes were present. In the five areas sampled here (Fig. 1), 83 Millennium classes were present. Thus 39 specific Millennium classes particular to the atoll clusters made of (i) Entrecasteaux, Beautemps–Beaupré and Ouvéa (23 classes); (ii) and the Zone Côtière Est and the area of Grand Lagon Nord (16 classes) were excluded from the present sampling. Finally, among the 83 Millennium classes present in the five sampled areas, 35 were actually sampled. The moderate ratio 35/83 (41%) of thematic representation is a consequence of the final site selection criteria which favored coral zones in reef framework. Sedimentary and lagoonal areas were not prioritized and not included in the final selection step and limited the diversity of sampled classes.

3.2. Habitat and fish community characteristics

3.2.1. Habitat typology

The analysis of the clustering of habitat data identified four main clusters (Fig. 5) with significant differences in average habitat

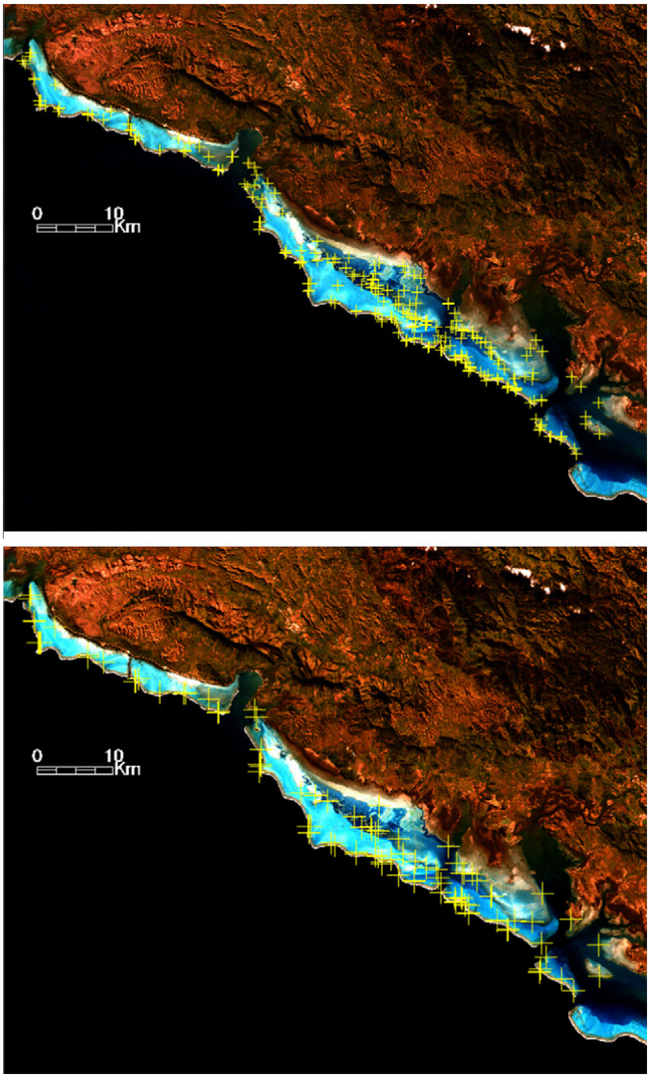

Fig. 4. Overlaid on a Landsat image, optimal (top) and simplified (bottom) selection of sampling sites (shown as yellow crosses) for Moindou–Bourail areas in the Zone Côtière Ouest cluster, with 249 and 104 sites respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

characteristics (Fig. 6). High average percent cover of macroalgae and coralline algae and very low average percent cover of bare rock characterized the first habitat type (10 stations). Coralline algae, rubble, and high average percent cover of bare rock characterized the second habitat type (31 stations). Fragile live coral forms (branching, foliose and tabular) with low levels of bare rock characterized the third habitat type (19 stations). Lowest sand cover and very high levels of bare rock with massive and encrusting coral forms and soft corals characterized the last habitat type (43 stations).

Spatially, the distribution of the different habitat types was not dependent on the sampled areas except for the first habitat type which was predominantly observed around the Ile des Pins (9 of the 10 stations of group 1). Habitat types were weakly related to the geomorphological classes regardless of the area (Fig. 5). Considering broad traditional geomorphological classes, namely oceanic slopes, lagoonal slopes, reef flats, inner side of barrier reef, lagoonal submerged reef, and fringing reefs, a larger proportion of oceanic outer slopes and reef flats were found in habitat types 4 and 3 respectively (Fig. 5).

In summary, keeping in mind that the site selection process prioritized shallow (0–15 m) coral growth zones in reef framework, Figs. 5 and 6 show that:

- habitat type 1 found in Ile des Pins was characterized by high algal cover (crustose coralline and more remarkably fleshy macroalgae) and could be predominantly found in oceanic forereefs and inner barrier reefs;
- habitat type 3 with high abundance of fragile coral growth forms were predominantly characteristics of reef flats, and found across all areas;
- the habitat type 4 with low abundance of sand and high abundance of bare rock substrate, soft corals and robust hard coral growth forms were predominantly found on exposed, energetic, oceanic and lagoon slopes, and found in all areas.
- the habitat type 2 appeared as a variation of the type 4, with high coralline and bare rock cover and sediment (rubble and sand), found predominantly on moderate energy environment (slopes and submerged reef, but also inner barrier reef), and found in all areas.

3.2.2. Fish community structure

The surveys censused a total of 308 species among the 311 listed beforehand as indicator or commercial species of interest. The analysis of the structure of the fish data also revealed four main communities or fish assemblages (Fig. 7). Soft coral, coralline algae, rock, submassive and digitate coral, massive and encrusting coral are five habitat factors that significantly discriminate fish assemblages (Table 1 and Fig. 8).

The first fish assemblage (32 stations) was mainly found where high average percent cover of bare rock characterized the habitat, thus corresponding to the forereef habitat in habitat types 4 (24 stations) and 2 (8 stations). The second fish assemblage (49 stations) was not significantly linked with the habitat factors selected by the CCA. The third fish assemblage (8 stations) was mainly found where soft corals and massive and encrusting corals were the most abundant percent cover and bare rock the lowest percent cover, thus found in habitat type 4 (6 stations). The last fish assemblage was found where coralline algae and submassive and digitate corals (the last category being non- significant in the determination of habitat types) were the more abundant percent cover. It was observed on habitat types 2 (6 stations), 1 (4 stations) and 3 (3 stations).

Spatially, the distribution of the different fish assemblages was not completely linked to the sampled areas, but specificities exist. For instance, no type 3 fish assemblages were observed in Corne Sud and Merlet, and no type 4 fish assemblages were observed in Merlet and Zone Côtière Ouest (Fig. 7). Thus, these two fish assemblages were found in only 3 of the 5 sampling areas.

Finally, fish assemblages were partially related to geomorphology (Fig. 7). Fish assemblages 1 and 2 were ubiquist and observed in all six broad geomorphological classes, the oceanic influence being more important for fish assemblage 1. Fish assemblage 3 was not observed on the inner barrier reef or on the reef flat. Fish assemblage 4 was not observed on the fringing reefs, the lagoon slopes and the submerged reefs.

4. Discussion

Two aspects need to be discussed regarding the reproducibility of our methods: (i) image interpretation and (ii) the general application of our approach to other UNESCO World Heritage Sites, and conservation programs in general.

One of the most recurrent criticism of photo-interpretation-based work is that results may vary between operators. Reproduc-

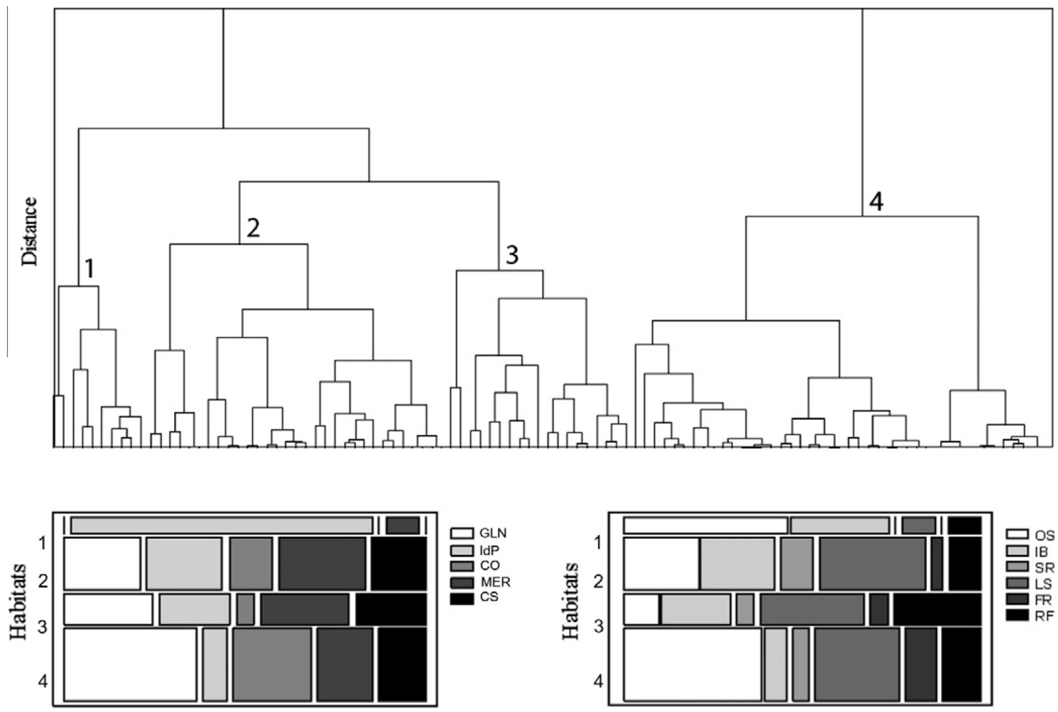

Fig. 5. Top: clustering of the stations according to habitat characteristics. Bottom: distribution of the five sampled areas (left) and the main geomorphological classes (right) within the fours types of habitat (numbered 1–4) identified by hierarchical clustering. GLN, Grand Lagon Nord; IdP, Ile des Pins; CO, Zone Côtière Ouest; MER, Merlet; CS, Corne Sud; OS, outer slope; IB, inner barrier reef; SR, submerged reef; LS, lagoon slope; FR, fringing reef; RF, reef flat.

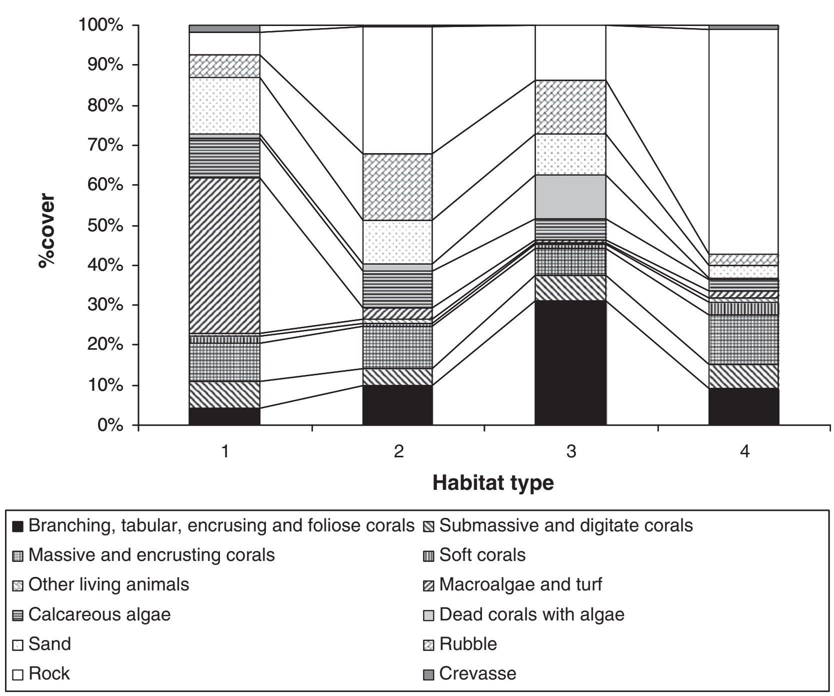

Fig. 6. Average characteristics of each of the four broad habitat types in the main 12 benthic categories.

ibility is therefore often deemed impossible. There is obvious variability depending on expertise and skills. Here, however, photo-interpretation skills requirements were actually limited. The task was not to thematically label a polygon, which indeed requires expertise, but more simply to identify different areas based on color and texture (Fig. 2). Therefore the task required no expertise in terms of reef habitats and their image signatures but instead the need to be systematic in decision making. It is true that within a geomorphological-color-texture stratum, different sites could be picked up by different operators, or even by the same operators during two different working sessions. This is not an issue as it naturally provides a random-stratified sampling scheme. Obviously, once strata have been spatially limited, a program could be run to randomly select sites without human intervention. Beforehand,

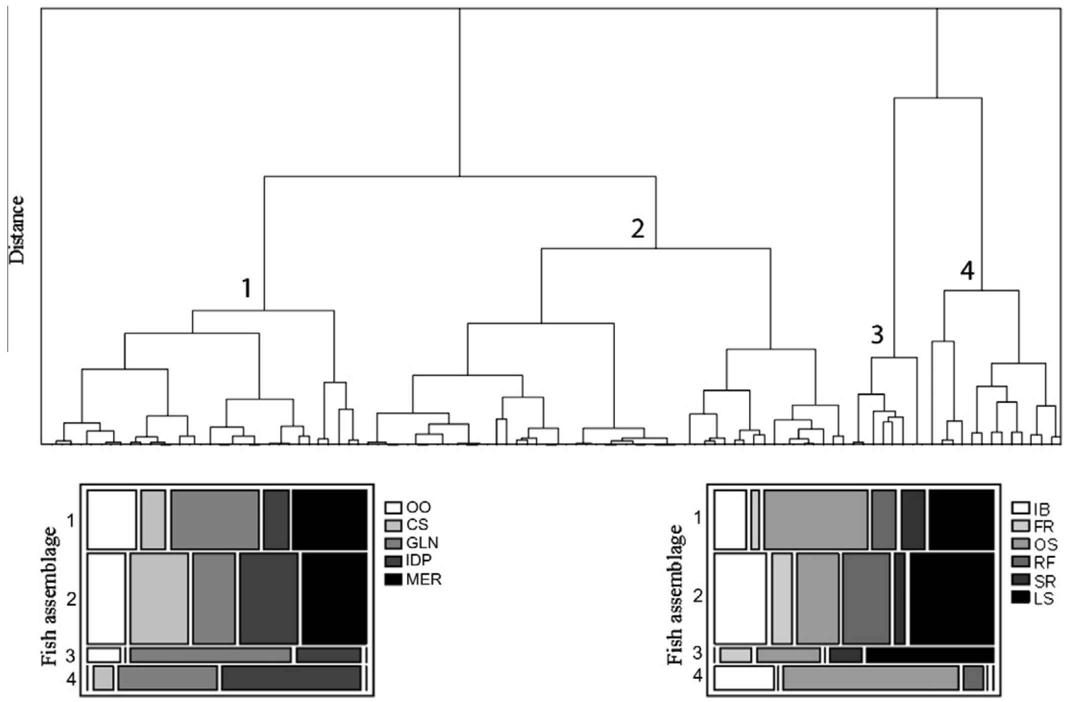

Fig. 7. Top: clustering of the stations according to fish assemblages as determined by canonical canonic analysis scores. Bottom: distribution of the sampled areas (left) and the geomorphological classes (right) within the fours four fish assemblages identified (numbered 1–4). GLN, Grand Lagon Nord; IdP, Ile des Pins; CO, Zone Côtière Ouest; MER, Merlet; CS, Corne Sud; OS, outer slope; IB, inner barrier reef; SR, submerged reef; LS, lagoon slope; FR, fringing reef; RF, reef flat.

Table 1
Summary of the canonical correspondence analysis (CCA) on the density of fish species per station.

Axes		1	2	3	4
Correlations fish-habitat		0.79	0.75	0.70	0.65
Cumulative percentage variance of species-environment relation		37.8	58.3	75.8	88.6
	Significant habitat classes			*p*-Value	
1	Soft coral			0.005	
2	Coralline algae			0.005	
3	Rock			0.005	
4	Massive and encrusting coral			0.005	
5	Submassive and digitate coral			0.04	

strata could be defined by using Millennium polygons with automatic unsupervised classifications based on color and texture (Wabnitz et al., 2008). However, unsupervised classification algorithms require the *a priori* definition of the number of classes, which may not be available easily, and can not be defined without an initial photo-interpretation analysis.

The goal of the scheme applied here was to characterize synoptically a large World Heritage Site to ideally provide a representative and exhaustive view of its habitats and its communities (of fish at least). The prohibitive sampling required to be truly exhaustive forced us to simplify the scheme, and only include habitats from a narrower domain, specifically from coral growth zones found in reef framework. As such, 41% of the Millennium classes found in the sampled area were covered. It is important to underline that the scheme proposed here provides a reference point against which the actual sampled sites can be compared. Thus, their representativity becomes explicit and can be quantified. However, this representativity can be measured only in terms of geomorphology, spatial coverage, and color-texture patterns, i.e., using information that comes from remote sensing images.

Without further existing knowledge, it is obviously more difficult to assess how much is missed in structures that can only be described *in situ*, and not from images. However, New Caledonia fish communities have been well studied in the past and points of comparisons are available (e.g. Wantiez et al., 1997; Chateau and Wantiez, 2005; Kulicki, 2006; Wantiez et al., 2006; Fricke and Kulbicki, 2007). For instance, here, we observed 308 of the 311 targeted fish species (99.0%) present in a pre-established list of commercial and indicator species compiled beforehand from many previous studies. The characteristics of the different reef fish assemblages and their links with habitat variables are also consistent with reports from these previous studies (Kulbicki, 1997; Sarramégna, 2000; Chateau and Wantiez, 2005; Wantiez et al., 2006).

The habitat typology in four broad classes provided three broad but well contrasted classes, and one transition class (class 2). Details not presented here within each cluster also capture a wide gradient in benthic composition [fleshy algae (0–32%), coralline algae (0–44.2%), sand (0–58%), rubble (0–55%) and rock (0–87.6%), hard coral cover (0.8–71.4%), and soft coral cover (0–15.8%)]. Another way to demonstrate that a large gradient of habitat has been captured is that 8 of the 12 broad classes of recorded benthic categories discriminate the different habitat types. Furthermore, Ile des Pins was described as a distinct area in New Caledonia, due to a more temperate influence, with flora from both tropical and high latitude environments (Payri and Richer de Forges, 2007). This is corroborated by our findings with one habitat type (type 1) specific to Ile des Pins. The applied scheme was thus efficient in capturing relevant variations that contribute to the diversity and specificities of New Caledonia's reefs.

The tool developed here proves to be useful to allow quick implementation of a large-scale sampling that allows comparisons between sites, while in the same time provide a large-scale initial view of the habitat and communities to serve as a baseline for future monitoring. We feel that our approach could be easily implemented at other UNESCO World Heritage Sites or any other marine

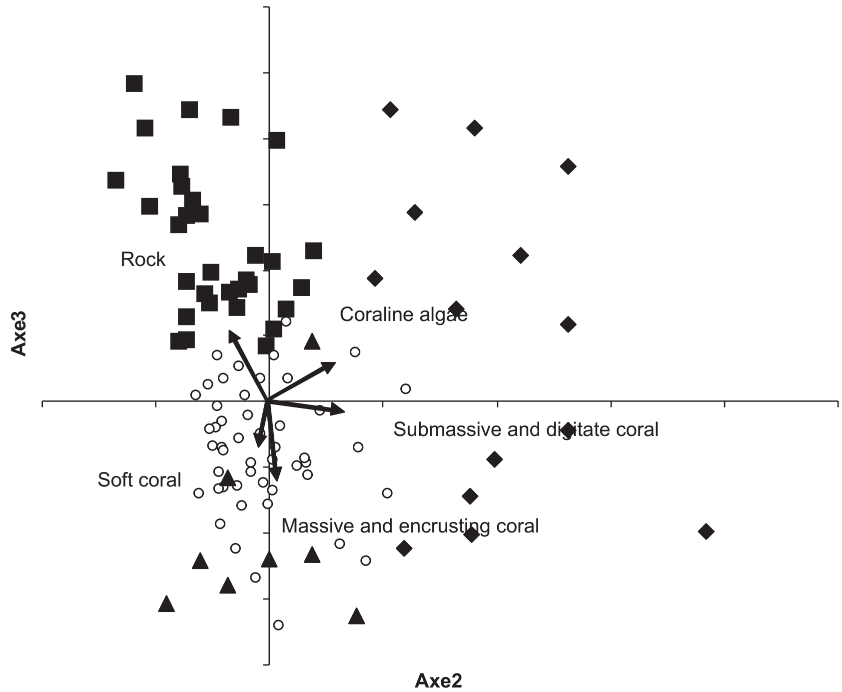

Fig 8. Plans 1–3 of the stations from a canonical canonic analysis on the density of the fish species per stations according to the habitat characteristics. Only the significant habitat classes are represented. Black square (■), fish assemblage 1; white circle (○), fish assemblage 2; black triangle (▲), fish assemblage 3; black diamond (♦), fish assemblage 4.

site worldwide since Millennium maps cover a large array of countries, and remotely sensed imagery are now common and often easily available (e.g. http://oceancolor.gsfc.nasa.gov/cgi/landsat.pl for Landsat data and the MCRMP archive). However, *in situ* surveys are site specific and could usefully target more taxa than what we did here only for fish communities.

5. Conclusion

To include new coral reef areas into the prestigious list of UNESCO World Heritage Sites, it is necessary to demonstrate in a limited amount of time the unique environmental value of the candidate areas. For large areas, the challenge can be overwhelming if no baseline data are available. In this study, based in New Caledonia and for which limited datasets were on hand, we proposed an assessment scheme driven by remote sensing. This allowed to maximize habitat diversity in the sampling, with a second step necessitating compromise and simplification due to logistical constraints.

The hypotheses that drive this protocol were inspired by numerous mapping projects that previously demonstrated the power of imagery to identify a large variety of habitats (Andréfouët, 2008). The scheme was accepted and implemented by the New Caledonia Committee in charge of the UNESCO case. We presented here the variability of structures observed in terms of habitat and fish communities from five large areas that covered a 600 km-long latitudinal gradient. Both new results and previously published data suggest that coral habitats and fish assemblages described with this protocol offer a diverse and representative view of the patterns present in New Caledonia. Here, we do not conclude on the quality of habitats and fish communities. This is beyond the scope of this paper meant to emphasize diversity and representativity. Quality and status of habitats and fish communities could be described at a later point.

We further suggest that a similar scheme can be applied anywhere new assessments are needed, in a World Heritage Site context, but also for any conservation program focusing on large areas. Other sampling designs and criteria are obviously possible. For instance, one may design a scheme driven by a gradient of environmental risks and disturbances (fishing, pollution, proximity to human populations, etc.) rather than a gradient of habitat diversity as seen via remote sensing imagery. However, we believe remote sensing is an efficient and practical mean to precisely select sites and assess their representativity. It may well be the only means to drive similar operations in remote and data-poor places worldwide. Since it is important and desirable that more coral reef areas are added to the UNESCO World Heritage List and other conservation frameworks, we hope that the scheme proposed here will help guide other applications worldwide.

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