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 km² 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 significance. 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 km² 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-Beauté-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),
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 MCRM 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 ade-
quate 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 config-
urations, 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 opti-
cal 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 representa-
tivity/exhaustivity criteria (Andréfouët, 2008). The rationale for
using raw imagery vs some form of pre-interpreted maps or unsu-
ervised 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 sur-
vey, 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 cre-
ated against which the representativity of the actual survey can be
tested. Simplifications can obey the following different criteria, ap-
plied in separate iterations:

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

2. **Thematic exhaustivity**: at least one site for each habitat needs to
be included;

3. ** Rarity**: the rarest and most unusual configurations are priori-
tized;

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 sim-
plications based on criteria 5 and 6 meant that the surveys would
focus on coral rich habitats found on reef frameworks. This simpli-
ification 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 la-
ter 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 Sci-
ence (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 belong-
ing 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; macro-
algae and turf; other living animals; dead corals with algae; calcar-
eous algae; sand; rubble; rock; crevasse. The percentage of each
substrate category at each station was calculated by:

\[
\%_i = \frac{100 \times L_i}{L_T}
\]

where \(\%_i\) is the percentage of substrate category \(i\); \(L_i\) is the total
length of category \(i\); 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 Sarramégnà, 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 Sarramégnà, 1999):

\[
D = \frac{\sum_{i=1}^{n} r_i d_i^{1.5}}{2L_T}
\]
where $D$ is the density ($\text{fish m}^{-2}$); $n_i$ 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:

$$d_i = \frac{1}{n_i} \sum_{j=1}^{n_i} n_j d_{ij}$$

where $n_i$ is the number of occurrences of species $i$; $n_j$ is the number of fish of species $i$ observed at occurrence $j$; $d_{ij}$ 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 (Beaupré–Beaupré–Beaudet) 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 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, Beaupré–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 lagoon 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
Spatially, the distribution of the different habitat types 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.

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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,
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%), 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...
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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