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Comparison of visual census and high definition video transects for monitoring coral reef fish assemblages

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Abstract:

Monitoring fish and underwater habitats, particularly in and around marine protected areas (MPAs) requires non-destructive observation methods. This is generally achieved by divers conducting underwater visual censuses (UVC), but video-based techniques are now being used more often to observe underwater macrofauna and habitats. A comparison of these two techniques is relevant with the development of high-definition (HD) video, which constitutes a substantial improvement over previously available video resolutions at limited extra cost. We conducted a paired observation experiment involving both HD video and UVC in an MPA located in the New Caledonian lagoon, which is a highly diversified coral reef ecosystem. We compared three techniques for counting fish along 50 m × 4 m delineated strip transects: UVC and two video techniques in which the diver used either a straight trajectory (I-type transect) or a browsing one (S-type transect). The results showed that the proportion of fish that were not identified up to the species level did not exceed 3.3% in video observations versus 1.7% in UVC. The abundance and species richness were larger in UVC than in videos, and S-type transects detected more individuals and species than I-type transects. The average abundance and species richness observed by UVC were 1094 individuals and 69.7 species per transect respectively. In comparison with UVC, I-type and S-type video transects detected on average 56% and 61% of the abundance and 85% and 77% of the species richness seen by UVC respectively. Our results showed that, in comparison to UVC data recorded in situ, the post field analysis of HD video images provided representative observations of fish abundance and species diversity, although fewer species and individuals were detected.

The advantages and shortcomings of each observation technique for monitoring fish assemblages, particularly in an MPA are discussed. HD video appears to be a cost-effective technique in terms of the human resources and time needed for field implementation. Overall, this study suggests that HD video-based techniques constitute an interesting complement to UVC, or an alternative when these cannot be implemented.

Keywords: Fish assemblages; MPA monitoring; High-definition underwater video; Underwater visual censuses (UVC); Coral reefs

1. Introduction

Coral reef ecosystems are characterized by their level of species diversity, which is among the highest of world's marine ecosystems (Connell 1978; Ray 1988). Recent reports on the condition of coral reefs warn of their ongoing degradation (Wilkinson 2004). This situation requires the implementation of management measures aimed at i) preserving the biodiversity of coral reef ecosystems and ii) sustainable development of the activities that depend on these ecosystems. Marine protected areas (MPAs) are a key management instrument for achieving these two objectives, and quantitative targets have been set for a global network of MPAs in the coming years (Convention for Biological Diversity (CBD), http://www.biodiv.org/defaults.html). With these recommendations comes the obligation to establish monitoring programs to track the progress toward the achievement of biodiversity conservation, based on tools that do not disturb the ecosystem. Therefore, monitoring and assessment of fish and their habitat in particular in and around highly protected MPA require non-destructive observation methods. This is generally achieved by underwater visual censuses (UVC) which have been successfully used for years to estimate reef fish abundance or biomass in studies of population dynamics, ecology and management (e.g., Barans and Bortone, 1983; Samoilys, 1997; Samoilys and Carlos 2000; Bortone et al., 2000). The advantages and disadvantages of this method have been summarized in several papers (Harmelin-Vivien et al. 1985; Harmelin-Vivien and Francour 1992; Cappo and Brown 1996; Samoilys 1997; Willis et al. 2000; Watson et al. 2005). For example, some "shy" or cryptic species are not accurately observed because they avoid the presence of the divers conducting the census (Kulbicki 1998; Watson et al. 1995, 2005; Stewart and Beukers 2000; Willis and Babcock 2000, Willis 2001).

UVC requires experienced divers that are trained for identifying species and estimating individual fish sizes. For the purpose of MPA monitoring, managers often prefer methods that do not require experienced divers and that can be implemented by MPA staff. In the last fifteen years, video-based techniques have become commonly used tools for observing underwater macrofauna and habitat, in particular for fish (Michalopoulos et al. 1992; Potts et al. 1987; Tipping 1994, Tessier et al. 2005, Watson et al. 2005). UVC and video techniques, whether remote or diver operated involve distinct costs in the field and in the laboratory. These can be compared using cost-benefits analyses, such as the study by Langlois et al. (2010) who compared two stereo-video techniques across tropical and temperate systems.

High definition (HD) video is a recent and substantial improvement over previously available resolutions at little extra cost, but it is still rarely used for underwater ecological observations compared to UVC. Harvey et al. (2010) found that a HD stereo-video system gave better precision and accuracy of length measures compared to a standard video system.

Here we do not intend to compare HD video with standard video because HD video is becoming that standard in both consumer and professional video systems.

Therefore, we investigated the value of using HD video techniques versus UVC for observing fish assemblages in a highly diversified coral reef ecosystem of the South Pacific. For this purpose, we conducted a paired observation experiment involving both video transects and UVC transects in an MPA located in the New Caledonian lagoon. Our interests were two-fold: i) to compare UVC and HD video, and ii) comparing rapid video transects versus longer video transects for the purpose of monitoring. Here, we report our findings from this experiment, and discuss the advantages and shortcomings of each observation technique for monitoring highly diversified fish assemblages such as those encountered at coral reefs and particularly in MPAs. Cost-effectiveness issues are also discussed.

2. Methods

2.1. Observation protocol

The study area was located in the Southwest Lagoon of New Caledonia, South Pacific. The lagoon encompasses a network of marine reserves including reefs and islets. Our experiment was conducted around Signal Island, which has been protected from all fishing since 1989 (Fig. 1). Three sites located on the reef were selected that correspond to habitats with distinct complexities in shallow areas at a depth of 3 to 5 m. Within each site, we delineated three 50 m long and 4 m wide transects using a measuring tape. For habitat analysis, five segments of 10 m x 4 m were delineated within each transect. In each transect, we carried out both UVC and video observations. UVC were performed by swimming slowly and pausing for fish identification and counting when needed. For each UVC, all individual fish in the transect were identified and counted underwater, and their size was estimated. Two types of video observations were conducted: i) where a diver swam through the transect in a straight line, at a constant speed (ca. 0.2-0.3 m.s^{-1}) and elevation (ca. 1.5 m above the bottom), the camera pointing at an approximate angle of 100° with the water surface (I-type transect); and ii) where the diver browsed inside the transect area in a similar fashion to the diver conducting the UVC transect, at varying elevation, speed, and angle and zooming when needed (S-type transect).

The elevation chosen for I-type transects enabled the wide angle of the camera to capture the entire width of the transect. In browsing transects (S-type) and in the UVC, the diver could look in any direction, stop and change their elevation.

I-type transects lasted on average 4 min 30 s, while S-type transects lasted on average 10 min and UVC lasted between 45 and 60 min. There were at least 5 min between any two successive observations. Observations were thus considered as independent. We aimed at testing the effect of the transect type (straight video, browsing video and UVC) as well as the effect of carrying out the video observations before or after the UVC. For this purpose, we successively performed in each transect one video observation of each type, one UVC observation and then another video observation of each type. For the pairs of video observations conducted either before or after the UVC, the order of the video transect type was randomized. Therefore, our experimental design crossed three levels of “transect type” with two levels “before/after”.

Video images were obtained using a HD Sony™ camera HDR-SR1 with an integrated hard drive of 30 gigabytes enabling up to 4 hr of HD images to be collected. The camera records a signal that follows the 1080i standard, i.e., with a resolution of 1920X1080 pixels (Full HD), and that is saved on the internal hard drive using the AVCHD™ format which is based on the MPEG-4 AVC/H.264 for image compression. The housing and lens resulted in an approximate focal angle of 60°. No artificial light was used. Images were analyzed on a 22' screen by the same fish expert that carried out the UVC, using standard viewing software that enables slow view and zooming, such as PowerDVD[1] or the Nero Suite[2]. All fish were identified and counted per species and size class. Size classes were small, medium or large. Class boundaries were defined by UVC divers to ensure that the size classes used for video were consistent with UVC observations. Image analysis was conducted several weeks after the field work so that the UVC observations did not influence the analysis.

For each transect at each site, habitat was characterized from the images using the medium-scale approach (MSA) described in Clua et al. (2006). For each segment in each transect, the percent cover of biotic and abiotic components was recorded. Ten categories were considered for the abiotic components, and seven categories were defined for living hard coral (Table 1). Algae and sponges were not recorded because they were scarce in the study site. Values were then averaged over segments for each observation in a given transect.

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[1] PowerDVD (Version 9.0 Ultra). Cyberlink Corp. 2009.

[2] The Nero Suite (Version 9) Nero Ltd. 2009..

2.2. Data analysis

We first tested the effects of conducting the video transects before or after the UVC on the overall abundance and species richness per transect by fitting two-way ANOVA models to video transect data. The models (one for species richness and one for abundance) included a time (before or after) and transect type (I-type and S-type) factors. The before/after effect was tested using a t-test.

Next, we analyzed the abundance and species richness observed from UVC counts and from the two types of video transects. The tests and comparisons for this analysis were conducted by two-way ANOVA modeling of species richness and abundance, considering the site (three levels: site 1, site 2 and site 3), and transect type (three levels: UVC, I-type, and S-type). Using this method, we could predict the mean abundance and species richness per transect that can be expected to be observed by each observation technique, namely UVC and I-type and S-type transects. Our results were interpreted considering the differences in sites due to habitat, on the basis of the MSA description of habitat. For this purpose, the percent values of biotic and abiotic components of habitats were averaged over the transects of each site to provide information for between-site comparisons.

In a third step, we investigated the differences in fish assemblages observed from each observation technique. For each family, we first calculated the number of species and the abundance per transect. Then for each transect type, the overall means for both abundance per family and species number per family across transects were computed by averaging the previous values over transects of a given type. For a number of families that were observed in both a large proportion (more than 75%) of video observations and in all UVC observations, the abundance per family was modelled using a two-way ANOVA involving the site and transect type factors. Differences due to transect type could thus be statistically tested. For the other families, no test was carried out because the number of zero observations was too high to enable quantitative comparison.

3. Results

3.1. Fish identification

During the 36 video transects conducted, 37950 individual fish were observed corresponding to 182 species from 35 families. A number of fish could not be identified at the species level: 655 individuals were identified at the genus level, 592 individuals were identified at the family level, and 28 individuals were not identified at all. Overall, only 3.3% of all observed fish were not identified at the species level. Most fish that were identified at family level only corresponded to juvenile individuals belonging mainly to Scaridae (parrotfish) and Pomacentridae (damselfish) (80% and 17% of individuals identified at family, respectively). Similarly, most fish that were identified only at the genus level were represented by *Pomacentrus* and *Scarus* (67% and 26% of individuals identified at genus level, respectively).

In the 9 UVC transects, 11,394 fish individuals were observed, corresponding to 138 species from 29 families. Among these, all individuals were identified at the species level, except for 1.7% (200 ind.) that could only be identified at the genus level, most of which belonged to damselfish (77 ind.), parrotfish (65 ind.) and labrids (39 ind.).

3.2. Before/after UVC effect on video transects

For video observations, the difference in species richness or abundance due to transect type was larger than that due to timing of the video transect (Fig. 2). This was confirmed by three-way ANOVA fitted on these variables with site, transect type and before/after factors. Though the model of species richness was highly significant (adjusted R^2=0.47, F(11,24)=3.81 with p=0.003), the transect type effect was the only significant effect ($p=1.7.10^{-5}$) and the before/after effect was far from being significant (p=0.65). For abundance, the model with three factors was not found to be significant overall, but the model with only the transect type and the before/after factors was significant (adjusted R^2=0.2891, F(3,32)= 5.7 with p=0.003). In the latter model, the before/after effect was not significant (p=0.79) and the transect type effect was the only significant effect (p=0.00025). Therefore, conducting the video observation before or after the UVC was found to have no significant effect on the overall abundance and species richness that were detected per transect. We also compared the abundance per family observed before and after for a given transect type. The correlation coefficient between these two abundance values was 0.998 ($p<2.2.10^{-16}$). Two ANOVA models including the transect type, site, family, and before/after factors respectively fitted to the abundance and species richness per family confirmed that the before/after factor was not significant and did not interfere with the other effects. Non-identified individuals were excluded from the latter models, as well as Pomacentridae, because the distribution of corresponding data did not meet model assumptions when they were included.

Because the before/after effect was found not to be significant, it was not considered in the rest of the analysis.

3.3. Effect of transect type on the species richness and abundance per transect.

At each site (S1, S2, S3), the mean species richness per transect observed for each transect type was, respectively, (38.7, 38.5, 35.8) for I-type, (54.7, 45.8, 45.2) for S-type, and (69.7, 60.3, 63.7) for UVC transects. Mean abundances per transect observed at each site were, respectively, (612, 728, 704) for I-type, (932, 901, 1008) for S-type, and (1094, 1570, 1134) for UVC. The observed abundances and species richness were larger with UVC than with video, and S-type transects detected more individuals and species than I-type transects (Fig. 3).

We fitted a two-way ANOVA with transect type and site factors to both the overall abundance and species richness per transect. For species richness, the model was valid and highly significant (adjusted R^2=0.77, F(8,36)= 19.2 with $p<7.10^{-11}$), and only the effects of the transect type and site were significant ($p<4.9.10^{-13}$ and $p<9.10^{-3}$, respectively). For the abundance and species richness, the adjusted R^2 were 0.58 and 0.62, respectively; the F(8,36) statistics were 8.5 ($p<2.1.10^{-6}$) and 9.95 ($p<3.5.10^{-7}$), and the only significant effect found was due to transect type ($p<5.9.10^{-8}$ and $p<2.4.10^{-9}$, respectively). In both cases, the interaction between site and transect type was not significant, indicating that differences between the transect types did not depend on the site.

This model was used to predict the species richness, abundance and number of families per transect that can be detected by each technique (Table 2). The predicted average abundance and species richness obtained from UVC were 1094 individuals and 69.7 species per transect, respectively. The predictions of abundance and species richness for I-type video transects were 56% and 61%, respectively, of the abundance and species richness predicted for UVC, while for S-type video transects, they were 85% and 77% respectively of the predictions for UVC.

From UVC, the species richness appeared to be higher at site 1 than at the other sites, and the overall abundance was higher at site 2 than at the other sites (Fig. 3). Between-site differences in abundance and species richness may be attributed to differences in coral reef habitats (Table 1). Site 1 was characterized by a larger cover of living coral which were mostly massive coral, while site 2 exhibited much more debris cover than the other two sites (40% of debris versus ~13% at the other sites), with more branched coral than massive coral (63% of branched coral versus 26% and 50% at the other sites), and some table coral, causing this site to have a lower habitat rugosity. Site 3 was intermediate in terms of rugosity; it had more sand and dead coral than the other sites, but also contained a large amount of branched coral and some massive coral.

3.4. Results per family

Twenty-nine families were observed in the 9 UVC and 35 in the 36 video observations (Table 3). In the rest of this paper, only S-type video observations will be compared to UVC because they provide more complete observations than I-type transects. Because the number of S-type video observations conducted was twice that of the number of UVC, the total species richness and abundances cannot be directly compared. In terms of occurrences, Pomacentridae, Labridae, Scaridae, Chaetodontidae, Acanthuridae, Pomacanthidae, Nemipteridae, Mullidae, and Blennidae, were observed in either all or more than 89% of video observations. Serranidae, Gobiidae, Lutjanidae and Balistidae and Synodontidae were seen in more than half of the video observations. The other families were seen less often. Each of these families was seen in all UVC, except for Balistidae, Synodontidae, Gobiidae and Lutjanidae.

For each family, the mean abundance per transect and mean species richness per family were computed by averaging values computed at the transect level, which mitigates the effect of differences in transect numbers between techniques. The results indicated that the mean number of species per transect that were detected from UVC was larger than from the videos, except for Scaridae, Nemipteridae, Aulostomidae and Lutjanidae (Fig. 4). However, the number of species detected by video transects is relatively large and is not considerably smaller than the number detected by UVC, particularly for frequent families such as Pomacentridae, Pomacanthidae, Scaridae, Labridae, Chaetodontidae Acanthuridae and Blennidae. For 21 families out of 35, the mean abundance per transect was larger in UVC than in videos, though this difference was not large for 8 of these families. The reverse was true for 2 families, and abundances were similar for 4 families. For each family that was encountered in a sufficient number of video transects (more than 75%) and in all UVC transects (Table 4), a two-way ANOVA with transect type and site factors was fitted to the family abundance per transect. For all of the models presented, the fits were good, and the residuals conformed well to linear model assumptions. The interaction between the site and transect type was not significant (except for Pomacentridae), which indicates that transect types compared similarly across habitats, i.e., the comparison did not depend upon fish abundance. From these models, the abundance predicted by UVC was always larger than that predicted by video (Table 4). The predicted abundances were very similar for Pomacentridae and Nemipteridae, with video observations detecting 92% and 94%, respectively, of the UVC-detected abundance. For Chaetodontidae, Acanthuridae and Blennidae, UVC predictions of abundance were considerably larger than those from video, with video detecting 72%, 66% and 54%, respectively, of the UVC-detected abundance. For Scaridae and Mullidae, the abundance predicted by UVC exceeds by far that predicted from video, with video detecting 43% and 36%, respectively, of the UVC-detected abundance. For families with an occurrence in between 7 and 11 video transects (40 and 60% of video transects, Table 3), no model was fitted, but the UVC abundance was larger than the video abundance for Synodontidae, Tetraodontidae, Gobiidae, Lutjanidae and Penguipedidae, and the reverse was true for Balistidae. For families rarely encountered (in less than 40% of video transects, Table 3), our results should be interpreted with caution. Note that Lutjanidae were seen much more often in video transects than in UVC, but the mean abundance per transect was larger in UVC due to a school of individuals being encountered.

4. Discussion

4.1. Observations of the fish assemblage according to the technique used

Abundance and species richness were larger in UVC than in video observations, but the fraction of the fish assemblage that can be detected from video images is representative overall. The comparison between these techniques is discussed here with regard to species identification and fish detection taking into account fish abundance and habitat complexity.

First, the ability to identify species is one of the most frequent concerns raised about video techniques. It is often assumed that fish identification is difficult in 2-dimensional images. However, in the present study, the proportion of fish that were not identified up to the species level did not exceed 3.3% in videos versus 1.7% in UVC. This lower proportion for UVC may be due to the level of expertise of the divers, and the fact that these can pay more attention in the field for species that are difficult to identify. The almost equally low proportion of species identified in videos may be explained by the use of HD cameras and to a lesser extent to the large screen used for image analysis.

Additionally, for S-type transects, the camera was filming as close to the fish as the diver during UVC, thus making image analysis easier.

An advantage of video transects was that images could be re-analysed and observers could spend more time identifying an individual from the guide books and differentiate between species, thereby allowing for more individuals to be identified at species level.

The second possible difference in the data obtained by these observation methods concerns the detection of fish species and fish individuals. Overall, our findings indicate a larger number of fish observed in UVC compared to video, although the results depend on fish families. This finding may be explained by the fact that UVC lasted on average 3 to 4 times as long as S-type video transects. Thus more time was available to encounter individual fish underwater. Overall, the difference between UVC and video is larger for the abundance than for the species number. There are two possible hypotheses to explain this. First, in 2-dimensional images it is more difficult to estimate the number of individuals within a school than from direct underwater viewing, which might lead to lower abundance estimates from video compared to UVC. Second, assigning an individual to a given species from the video screen might lead to the distinction of more species if the identification is done with the help of a book. In addition, video observers have more time than divers to discriminate among species in a given school.

The observation time required clearly depends on the technique used, and additional time in the laboratory is necessary in the case of video, while more time is spent in the field for UVC. In this study, the overall video observation time including the time spent underwater and the time spent at the laboratory, was quite similar to UVC.

In the present study, the consequences of differences in the underwater observation time were mitigated by the fact that the transect area was distinctly delineated. For both S-type transects and UVC, the diver takes the time required to capture, either by eye or by the camera, all of the fish that can be seen at that moment within the transect area. Still, UVC requires more time underwater than S-type transects, because fish have to be identified and counted on-site. It is difficult to conclude which technique best estimates the true abundance and species richness because as the observation time underwater increases, the probability that a fish which is present in the vicinity of the transect enters or leaves the delineated area also increases, so there is an increased possibility of counting the same fish twice and of seeing more species, which is particularly true for mobile species. Indeed, the two techniques provide distinct estimates of abundance and species richness. However, the point of this study was to evaluate whether video transects provide representative information about the fish assemblage, compared to a widely used technique such as UVC. It is also important to consider that for a given technique, observation time always increases with the in situ abundance and diversity of fish and it will increase less for video than for UVC. The analysis time per video transect also dramatically changes from temperate to tropical regions (Langlois et al 2010).

The third point of comparison between these techniques deals with the importance of the habitat type in fish detection. In our study, observations were done in several habitats with distinct characteristics, and the differences between fish assemblages that we detected were not found to depend on habitat complexity. Where some species and/or families were found in larger abundances at some sites due to differences in habitat, the techniques used were equally successful in the habitats surveyed. The differences that we observed in fish abundance depended on the site for only one family (Pomacentridae), as there was a great abundance of this family at one of the sites. For the other families, the video and UVC techniques compared similarly irrespective of the habitat considered.

Comparing the two video techniques, S-type transects yielded much greater species richness and abundance than I-type transects. Conducting S-type transects implies to delineate the surface area to be surveyed with a tape, but permanent delineation enables to monitoring the same transects over years. Because transects areas were delineated in this study, we avoided the issue of estimating distance, which is an additional source of uncertainty for UVC and for video techniques when stereo video is not used (Harvey et al. 2004). The I-type transect was still tested because, as elevation and speed are standardized, it could be used in other instances without having to delineate the transect area, which allows for quicker monitoring. However, it appears that I-type video transects may not capture all of the fish present in the area in a way that enables subsequent identification and counting. Consequently, this type of transect might be useful for monitoring particular species, but not the entire fish assemblage.

Langlois et al. (2006) used another video technique, the baited remote underwater video (BRUV) in proximate sites within the same area (Signal Is.). 14 species were observed among which 5 Serranidae, 4 Lethrinidae, 2 Carcharhinidae and 3 Acanthuridae. In this study, the corresponding numbers of species observed were: i) for Serranidae, 5 species in videos versus 6 in UVC, ii) for Lethrinidae, 3 in videos versus 1 in UVC, iii) for Carcharhinidae, 1 in videos versus 0 in UVC, and iv) for Acanthuridae, 6 species in both videos and UVC. The number of carnivorous species observed in video and UVC was larger in our study, as additional species belonging to other families were seen. Abundances observed in BRUV cannot be quantitatively compared to the estimates obtained in the present study, as they are calculated in a different way. The number of observations in Langlois et al. (2006) was smaller than in this study, therefore species numbers cannot be directly compared. Nevertheless, the results suggest that the presence of divers underwater influences fish observation, particularly for key fished species.

Overall, our results demonstrate the relevance of the HD video technique used here and of S-type transects for conducting monitoring of fish assemblages and habitat.

4.2. Advantages and shortcomings of the techniques in terms of logistics

The differences between techniques mainly pertain to the diving time and level of expertise of the diver that are required (Table 5). With respect to human resources, UVC requires at least one fish expert diver in the field, while a video transect requires a single diver who does not necessarily need to be a fish expert. As security regulations often require two divers underwater, and one at the surface, if two cameras are available, the number of observations can be doubled using video. At the laboratory, UVC and video data can be input by a single person. Videos were preferably analyzed by two persons, one of whom was a fish expert, but because the capacity for both species identification and counting from moving images increased during this process, a single person became perfectly able to do the work alone. Building the capacity for image analysis required some training, which was relatively quick when the analysis was conducted together with fish experts.

With respect to expertise, video transects can be conducted by any diver once they are trained to use the camera, which is quite easy, and a given video transect can be analyzed for both fish and habitat. In contrast, UVC transects require expert divers. At least one diver has to be able to identify fish species, and two are often required in coral reef ecosystems when all fish species are counted, as was the case in this study. UVC transects are generally run twice, one for fish, one for habitat.

With regard to the time taken for a given transect, I-type transects and S-type transects take on average 4 min and 30 s and 10 min, respectively, in the field. At the laboratory, image analysis lasted from 45 min to 1 hr and 30 min in the present study, depending on fish abundance and diversity. In the field, a UVC takes between 45 and 60 min. At the laboratory, data input and validation require 10 to 15 min per transect. Therefore, S-type video transects and UVC are comparable in terms of the overall time required per transect. In terms of the time required for image analysis, our findings differ from those of previous investigators such as Francour et al. (1999), Cappo et al. (2003) and Stobart et al. (2007) who found that image analysis was the limiting factor for videos in the case of BRUV. This is probably due to the fact that image analysis is greatly facilitated with HD. In this case, it is also of note that the duration of a video transect conducted by a diver is shorter than that of a BRUV (10 min versus 30 min from Stobart et al. (2007) and Langlois et al. (2006)).

To summarize the advantages and shortcomings of the techniques used for observing fish assemblages (Table 6), UVC is a widely used technique, with experts around the world, but all species are not systematically identified by this technique in highly diversified ecosystems such as coral reefs. Indeed, many monitoring programs either require only information for some species or species groups, e.g., target species, or do not collect information at the species level, see e.g., the protocols recommended by the Global Coral Reef Monitoring Network (Hill and Wilkinson 2004). In addition, UVC only require data input after field work, unlike video-based techniques which require further image analysis. In our study, UVC led to the detection of significantly more fish individuals and fish species than video monitoring. The first advantage of video is that it does not require an expert in fish identification in the field, and hence, a non-specialist diver can operate the camera. Second, video reduces the time spent underwater, allowing for more observations to be conducted. Less time in the field implies lower field costs, which are always larger than laboratory costs. Third, habitat information is collected at the same time as fish information with video. Fourth, video images may be archived, and they may be analyzed by several persons, thus limiting potential observer effects, which are sometimes a shortcoming of UVC (Preuss et al. 2009). Finally, video may also be analyzed for other purposes, e.g., for habitat or for a subset of species of interest.

From this study, we thus conclude that HD video is a technique that is worth considering for observing and/or monitoring fish assemblages in highly diversified ecosystems such as coral reefs. Our results for habitat observations were not presented per transect, and further study is needed to evaluate the efficiency of this technique for habitat monitoring, but the image analyses that we carried out have already shown that habitat characterization is easier than fish identification and abundance estimation. Using the MSA approach described in this paper, it took at most 10 min to analyze a single transect for habitat (Pelletier et al., unpubl. data).

Standard video was not considered in this study because the extra cost incurred by using HD video compared to standard video is marginal in light of the overall cost of conducting underwater observations, whether they are visual or video-based. The main point of this study was to compare HD video to UVC which are currently the most widely used technique for observing fish assemblages. It appears that HD video might constitute an interesting alternative to UVC when these cannot be implemented, e.g., when no fish expert is available in the field. Additionally, relying on several kinds of observation for monitoring is always desirable (Willis et al. 2000; Cappo et al. 2004). However, both techniques share a common disadvantage, namely the presence of divers underwater (Table 6). Divers are known to disturb fish, particularly in fished areas (see references in Stobart et al. 2007), where fish behavior differs from behavior in

MPA, and this is a potential source of bias for assessing the effects of MPA on fish assemblages. An additional shortcoming of these diving-based techniques lies in the limited range of depth that can be investigated and the number of observations that can be conducted per diver. Therefore, investigating techniques that do not require the presence of divers underwater is a promising alternative. Remotely operated video stations have been used for this purpose (Watson et al. 2005, 2007; Willis et al. 2000, Willis and Babcock 2000, Westera et al. 2003) and are increasingly envisaged as a monitoring tool for MPAs (Pelletier et al. 2009; Stobart et al. 2007). These might be an interesting complement to UVC, for instance, BRUV is now widely used in Australia and New Zealand (Willis and Babcock 2000; Willis et al. 2000, Harvey et al. 2004) and in the Mediterranean (Stobart et al. 2007). Using BRUV, a large number of species have been observed in coral reef ecosystems (Cappo et al. 2007) and in other contexts (Stobart et al. 2007), and observations can be carried out in deep areas (Cappo et al. 2007). Other techniques for marine ecosystem monitoring are also currently under development, and we will concentrate on these in future studies.

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FIGURE CAPTIONS

Fig. 1. Study area. Three sites (indicated by flags) were selected along the reef slope on the leeward side of the Signal Islet, located in the south-west lagoon of New Caledonia, South Pacific (insert). From North to South, the three sites are respectively S3, S1 and S2.

Fig. 2. Boxplots of species richness per transect (in number of species per m^2 (top) and abundance density per transect (in number of individuals) per m^2 (bottom) per video transect type and per timing (before/after) with respect to UVC transect. ‘I’ and ‘S’ respectively denote I-type and S-type video transects, i.e. straight and browsing transects (see § 2.1).For each boxplot, the thick line in the box corresponds to the median value; the lower and upper limits of the box correspond to the 25% and 75% percentiles of the data. The plot whiskers extend out from the box to the most extreme data point which is no more than 1.5 times the interquartile range from the box and all values are plotted.

Fig. 3. Boxplots of species richness per transect (in number of species per m^2 (top) and abundance density per transect (in number of individuals) per m^2 (bottom) per site and transect type. ‘I’, ‘S’ and ‘V’ respectively denote I-type, S-type and UVC transects. I-type and S-type respectively refer to straight and browsing transects (see § 2.1). For each boxplot, the thick line in the box corresponds to the median value; the lower and upper limits of the box correspond to the 25% and 75% percentiles of the data. The plot whiskers extend out from the box to the most extreme data point which is no more than 1.5 times the interquartile range from the box and all values are plotted.

Fig. 4. Average species number per transect (in number of species per 200 m^2) for each family, for UVC (light grey) and for S-type video (dark grey) transects.

Fig. 1. Pelletier et al.

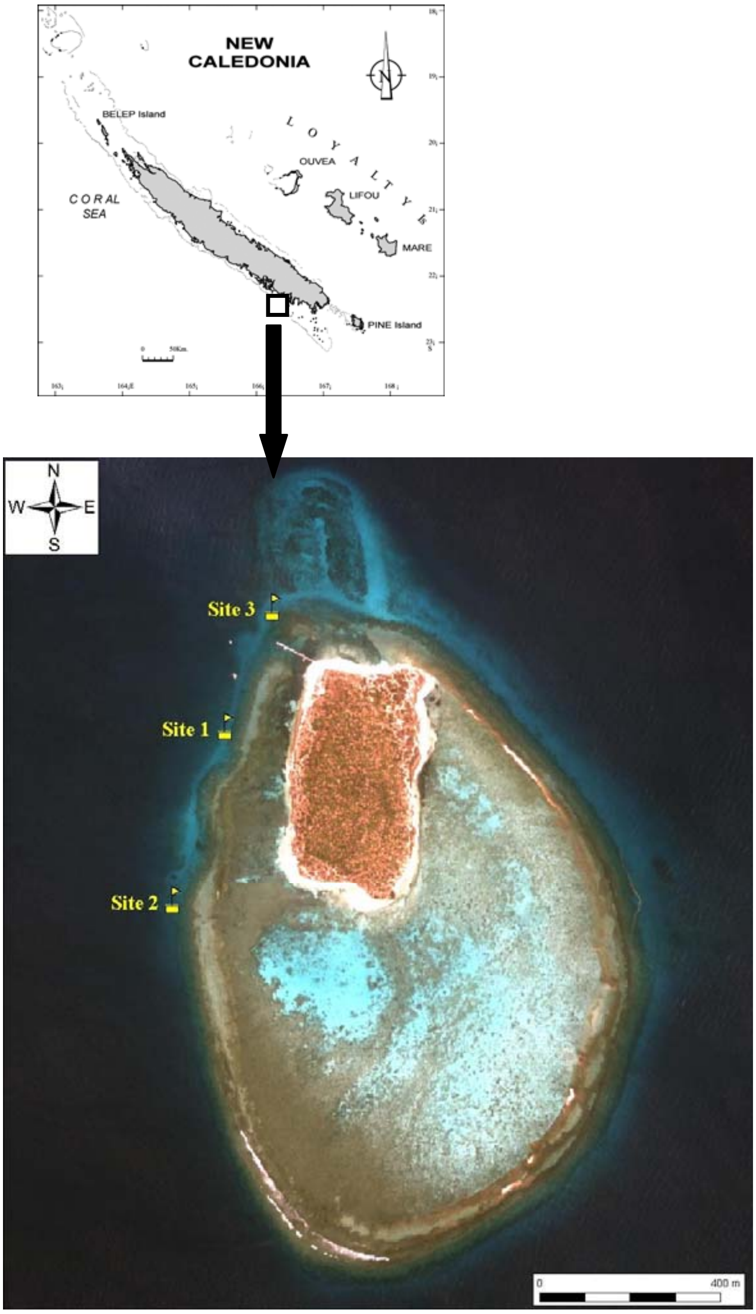


Fig. 2. Pelletier et al.

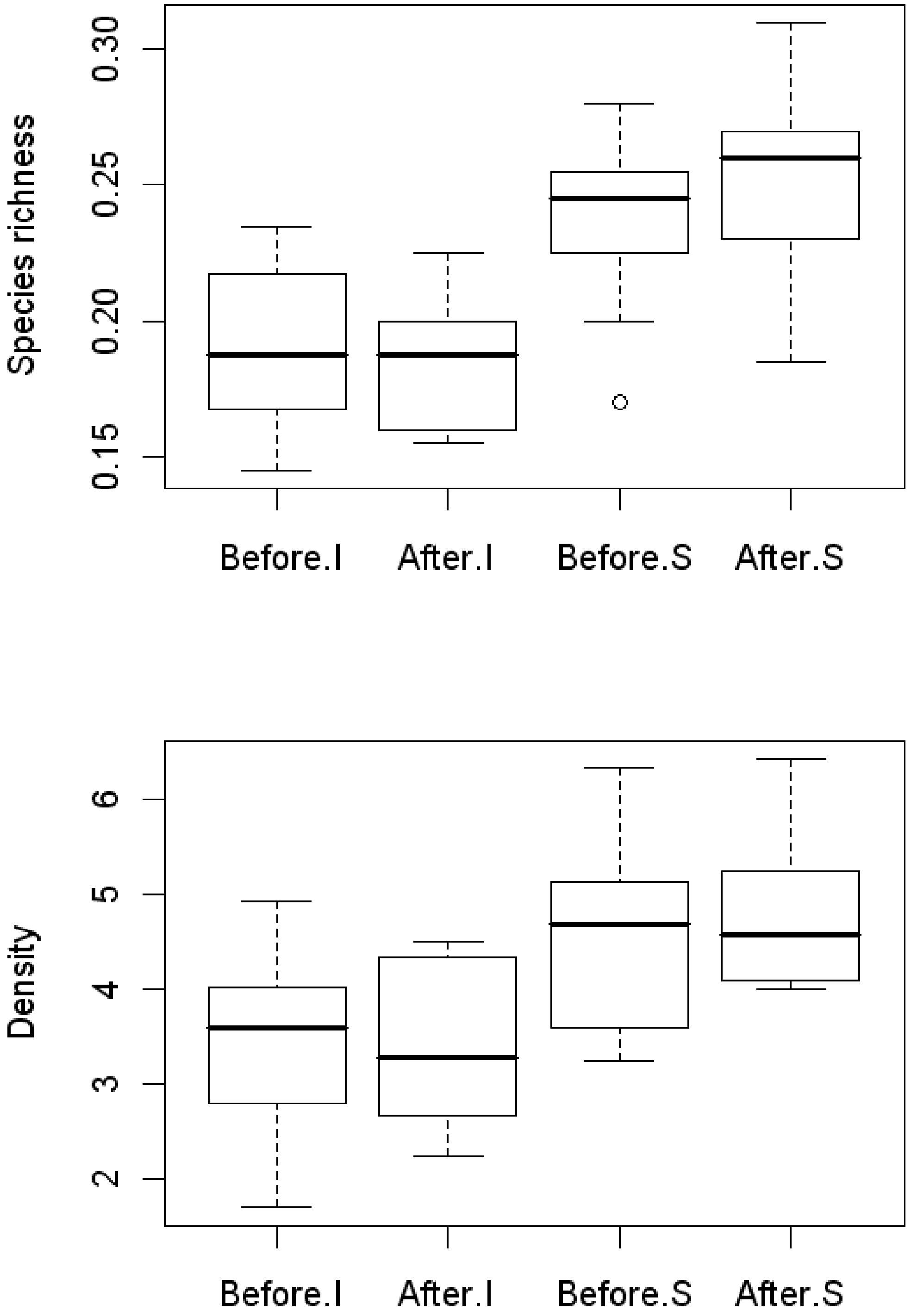
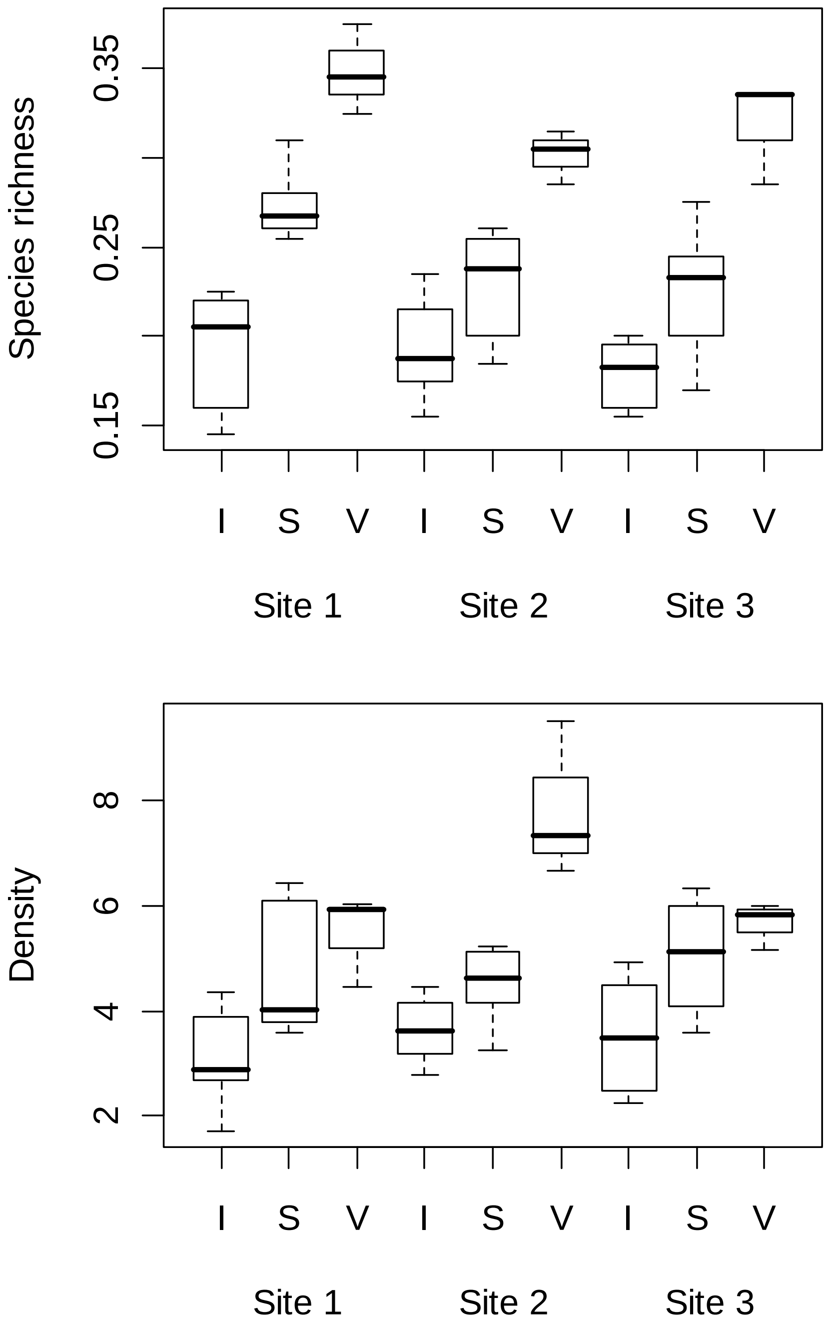


Fig. 3.


Species richness
0.15
0.25
0.35
I
S
V
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S
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I
S
V
Site 1
Site 2
Site 3
Density
2
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6
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Site 2
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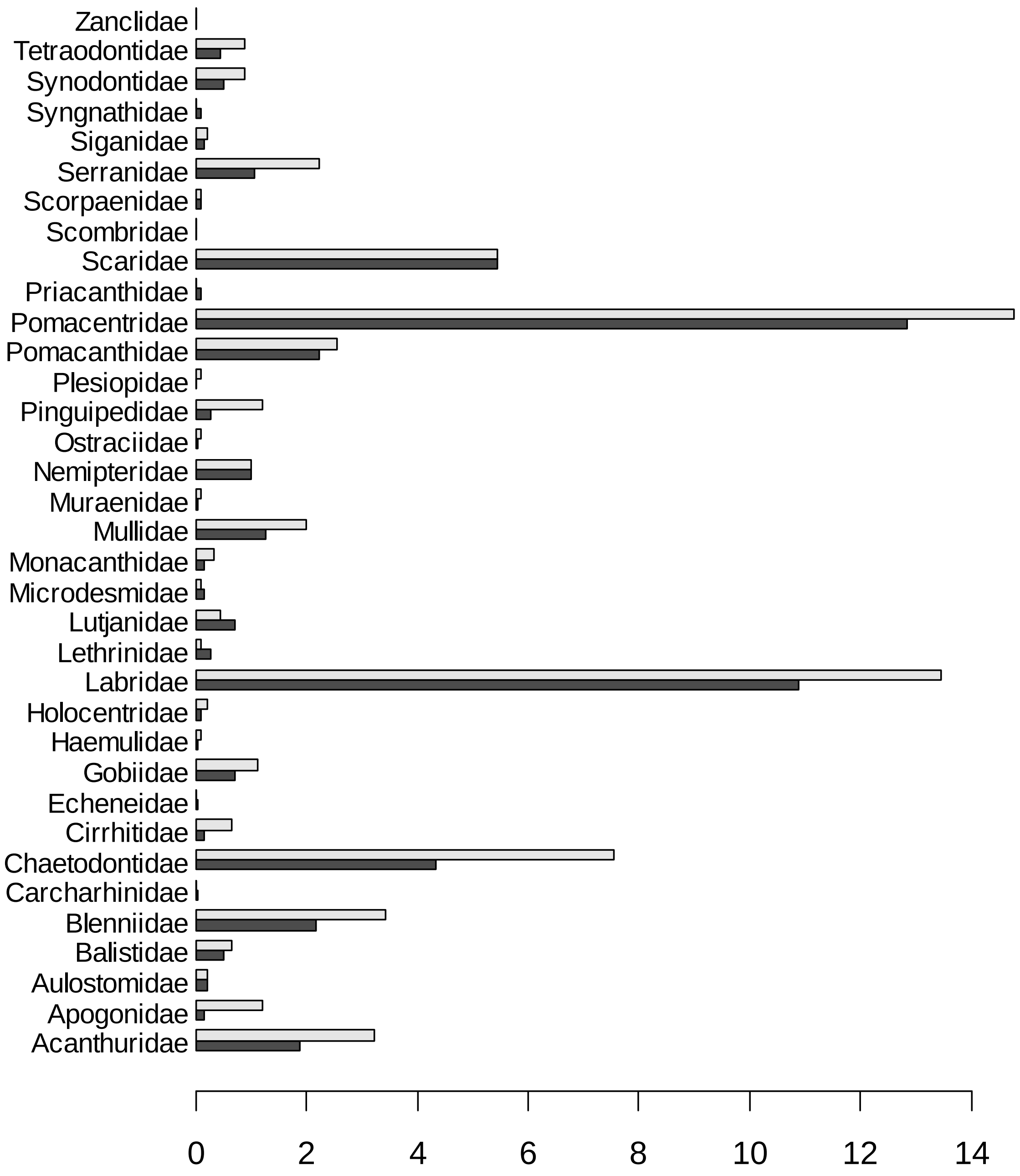

Fig. 4.   Pelletier et al.

TABLES

Table 1. Per-cent composition of abiotic and biotic cover at the three study sites, as recorded by the medium scale approach according to Clua et al. (2006). The per-cent covers sum to 100% for both general cover and for living coral categories inside the living hard coral component. Values larger than 10% are in bold.

	Site 1	Site 2	Site 3
General cover			
Mud	0.0	0.0	0.0
Sand	**22.1**	7.3	**25.4**
Debris	**12.5**	**39.3**	**13.3**
Small boulder	0.3	1.6	1.0
Big boulder	0.0	0.9	0.3
Dead coral rock	**29.0**	**15.2**	**28.5**
Coral skeleton in place	1.8	9.7	3.5
Bleached coral	0.0	1.8	0.8
Living hard coral	**28.5**	**19.9**	**25.0**
Soft corals	5.8	4.2	2.3
Composition of living hard coral			
Encrusting	9.1	5.8	9.9
Massive	**59.6**	9.8	**27.4**
Digitated	0.1	0.2	0.0
Branched	**26.3**	**63.3**	**49.7**
Foliose	0.0	0.0	0.0
Tabular	3.5	**20.7**	**12.8**
Millepora. sp.	1.4	0.2	0.2

Table 2. Prediction of average species richness, abundance and number of families per transect (per 200 m^2) for each observation technique from a two-way ANOVA with transect type and site factors. I-type and S-type refer to straight and browsing transects, respectively (see Methods section). For each technique, the average duration of an observation and the number of divers is given in parentheses.

Predicted metric	I-type video transect (1 diver, 4 min 30 s)	S-type video transect (1 diver, 10 min)	UVC (1 expert diver, 45-60 min)
Species richness	38.7	54.7	69.7
Abundance	612	932	1094
Number of families	12.5	15.1	18.4

Table 3. Number of occurrences (# occur.), density and number of species (sp. nb.) per family observed in the 18 S-type video transects and in the 9 UVC transects (S-type refers to browsing transects). Total abundance is the number of fish encountered over given types of transects. Mean abundance per family is computed by first adding individuals per family per transect and then averaging over the transects of a given type. It is expressed in number of individuals per transect surface area (each transect has a surface area of 200 m^2).

Family	# occur. (Video)	# occur (UVC)	Total sp. nb. (Video)	Total sp. nb. (UVC)	Mean abundance (Video)	Mean abundance (UVC)
Pomacentridae	18	9	31	29	803.3	1022.7
Labridae	18	9	28	22	44.6	66.2
Scaridae	18	9	11	10	37.2	57.1
Chaetodontidae	18	9	13	19	13.9	24.2
Acanthuridae	18	9	6	6	10.6	17.8
Pomacanthidae	18	9	3	3	9.9	18.2
Nemipteridae	18	9	1	1	6.1	6.3
Mullidae	16	9	4	4	3.9	6.8
Blenniidae	17	9	7	8	3.5	7.6
Serranidae	11	9	5	6	1.3	5.0
Balistidae	9	5	1	3	0.7	0.8
Synodontidae	9	8	1	1	0.9	2.1
Tetraodontidae	7	8	2	1	0.7	2.9
Gobiidae	11	8	3	3	1.1	3.9

Table 3 (continued)

Lutjanidae	10	3	7	2	6.1	8.6
Penguipedidae	4	8	2	2	0.5	4.7
Aulostomidae	4	2	1	1	0.3	0.4
Siganidae	3	2	1	2	0.4	0.3
Lethrinidae	4	1	3	1	0.3	0.2
Monacanthidae	3	3	1	1	0.3	0.9
Cirrhitidae	3	6	1	1	0.2	1.3
Apogonidae	2	7	2	4	0.3	6.7
Microdesmidae	3	1	2	1	0.2	0.2
Haemulidae	1	1	1	1	0.1	0.2
Scorpaenidae	2	1	1	1	0.1	0.1
Ostraciidae	1	1	1	1	0.1	0.1
Syngnathidae	2	0	1	0	0.1	0.1
Priacanthidae	2	0	1	0	0.1	0
Holocentridae	2	2	2	2	0.1	0.3
Muraenidae	1	1	1	1	0.1	0.1
Zanclidae	1	0	1	0	0.03	0
Carcharhinidae	1	0	1	0	0.06	0
Scombridae	1	0	1	0	0.007	0
Echeneidae	1	0	1	0	0.06	0
Plesiopidae	0	1	0	1	0	0.2

Table 4. ANOVA results for abundance per family for families frequently encountered (in more than 75% of S-type video transects and in all UVC transects) (S-type refers to browsing transects). Model assumptions were not met for other families. ‘Type’ stands for transect type effect while ‘Site’ stands for site effect. The effect linked to site 1 has no p-value attached as the coefficient is set to 0 by contrast options in the ANOVA model.

Family	Model significance Significant effects	Direction of effects and model predictions of abundance
Pomacentridae	R^2=0.48, F(8,36)=6.2 (p<6.10^{-5}) Type (p<5.10^{-6}) & Site*type (p<0.03)	More fish in UVC (p<0.01) More fish at site 2 in UVC (p<0.05) Video detects 92% of UVC abundance, but at site 2
Labridae	R^2=0.78, F(8,36)=6.2 (p<8.10^{-10}) Type (p<2.10^{-11}) & Site (p<2.10^{-4})	More fish at site 2 (p<2.10^{-3}) Video detects 68% of UVC abundance
Scaridae	R^2=0.69, F(8,36)=13.5 (p<9.10^{-9}) Type (p<7.10^{-5}) & Site (p<7.10^{-10})	More fish at site 2 (p<10^{-5}) Video detects 43% of UVC abundance
Chaetodontidae	R^2=0.44, F(8,36)=5.3 (p<2.10^{-4}) Type (p<5.10^{-6})	More fish in UVC (p<0.01) Video detects 72% of UVC abundance
Acanthuridae	R^2=0.71, F(8,30)=14.5 (p<5.10^{-7})	More fish in UVC (p<1.2.10^{-4})

	Type ($p<5.10^{-10}$) & Site ($p<5.10^{-7}$)	More fish at site 1 Video detects 66% of UVC abundance
Pomacanthidae	$R^2=0.64$, F(8,36)=11 ($p<2.10^{-7}$) Type ($p<6.10^{-7}$) & Site ($p<7.10^{-6}$)	More fish in UVC ($p<1.2.10^{-4}$) More fish at site 3 ($p<6.10^{-3}$) Video detects 47% of UVC abundance (6.3 vs 13.5 ind./tr)
Nemipteridae	$R^2=0.38$, F(8,36)=4.3 ($p<10^{-3}$) Type ($p<5.10^{-3}$) & Site ($p<5.10^{-4}$)	More fish at site 1 Video detects 94% of UVC abundance
Mullidae	$R^2=0.44$, F(8,36)=5.3 ($p<2.10^{-4}$) Type ($p<6.10^{-5}$) & Site ($p<6.10^{-3}$)	Video detects 36% of UVC abundance
Blenniidae	$R^2=0.59$, F(8,36)=8.8 ($p<1.4.10^{-6}$) Type ($p<2.10^{-2}$) & Site ($p<8.10^{-8}$)	More fish at site 1 Video detects 54% of UVC abundance

Table 5. Observation costs for the techniques used in this study. Observation time for fish corresponds to the identification of all species. For habitat, it corresponds to the implementation of the MSA approach (see Methods).

Technique		Staff required and approximate time per transect	Mean numbers of species and individuals observed per transect
UVC transect	In the field	1 or 2 fish expert divers 45 to 60 min (fish) 10 min (habitat)	64.6 species 1266 individuals
	At the office	1 person to input data 10 to 15 min	
S-type video transect	In the field	1 non-specialist diver 10 min	48.6 species 947 individuals
	At the office	1 fish expert 45 min to 1 hr and 30 min (fish) 10 min (habitat)	
I-type video transect	In the field	1 non-specialist diver 4 min 30 s	37.67 species 681.3 individuals
	At the office	1 fish expert 30 min to 1 hr (fish) 10 min (habitat)	

Table 6. Advantages and disadvantages of the techniques used for observing fish assemblages in reef ecosystems.

Technique	Advantages	Disadvantages
UVC Samoilys (1998) Harmelin-Vivien et al. (1985)	Widely used Most complete observation of fish assemblage Limited additional time at the office required	Requires qualified divers Diver effect on fish Observer effect on counts Additional field effort needed for habitat information Limited diving time and maximum depth
HD Video transects	Relatively complete observation of fish assemblage Reduced underwater observation time Simultaneous habitat information Limited observer effect (multiple image analysis) Images are archived	Diver effect on fish Takes additional time for image analysis Limited diving time and depth
Baited Remotely Operated Video (Willis and Babcock 2000; Cappo	In general relatively complete observation of fish assemblage, but better for carnivorous species No diver effect on fish No depth limitation Size estimation (if stereo video)	Uncertainty about the bait plume Takes additional time for image analysis

et al. 2003; 2004; 2006)	Images are archived